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Advanced-Technology Space Station Study: Summary of Systems and Pacing Technologies

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ABSTRACT

This report summarizes the principal system features defined for the Advanced Technology Space Station and describes the 21 pacing technologies identified during the course of the study. The descriptions of system configurations were extracted from four previous study reports. The technological areas focus on those systems particular to all large spacecraft which generate artificial gravity by rotation. The summary includes a listing of the functions, crew requirements and electrical power demand that led to the studied configuration. The pacing technologies include the benefits of advanced materials, in-orbit assembly requirements, stationkeeping, evaluations of electrical power generation alternates, and life support systems. The descriptions of systems show the potential for synergies and identifies the beneficial interactions that can result from technological advances.

ABBREVIATIONS AND ACRONYMS

AC	Alternating Current (amperes)
ATSS	Advanced-Technology Space Station
bps	Bits per Second
CG	Center of Gravity
CMG	Control-Moment Gyroscope
D	Deuterium, Hydrogen of Mass Number 2
DC	Direct Current (amperes)
E	Modulus of Elasticity for a Material, GPa (lb/in^2)
ECLSS	Environmental Control and Life Support System
EVA	Extravehicular Activity
FAB	Fabrication
F_{TU}	Ultimate Tensile Strength, Pa (lb/in^2)
g	Gravitational Acceleration of the Earth, 9.8 m/sec^2 (32.2 ft/sec^2)
GEO	Geosynchronous Earth Orbit
GN_2	Gaseous Nitrogen
HEO	High Earth Orbit
HLLV	Heavy Lift Launch Vehicle
I	Moment of Inertia, $kg\text{-}m^2$ ($slug\text{-}ft^2$)
$IDEAS^2$	Integrated Design Engineering Analysis Software - Interactive Design and Evaluation of Advanced Spacecraft
IVA	Intravehicular Activity
k	Radius of Gyration (m, ft)
ksi	Thousands of Pounds per Square Inch
LEO	Low Earth Orbit
m	Mass Element, kg (lb)
MBTF	Mean Time Between Failures

MMC	Metal Matrix Composites
Mops	Mega Operations per Second
MRMS	Mobile Remote Manipulator System
NaK	Mixtures of Sodium and Potassium that are Liquid at Ordinary Temperatures
OMV	Orbital Maneuvering Vehicle
OTV	Orbital Transfer Vehicle
psi	Pounds per Square Inch
RMA	Remote Manipulator Arm
T	Tritium, Hydrogen of Mass Number 3
Θ	Orbit Angle Measured from Solar Zenith, degrees
w	Rotational Velocity rad/sec

1.0 INTRODUCTION

The United States will operate a manned space station before the end of this century. This initial operational capability, designated Space Station Freedom, will be assembled in low Earth orbit (LEO) and have the capability of performing Earth observations, scientific studies, man-in-space evaluations, and commercial demonstrations. Space Station Freedom will expand in both size and concepts to meet new challenges and incorporate improved technologies. In the future, a manned space station will support other space flight missions, commercial activities and additional Earth and space observations. Consequently a substantially larger and more diversified platform will be required. A larger, advanced station would utilize the technological advances available at that time. This report addresses the prospective requirements, subsystem technologies, and operational concepts for an Advanced-Technology Space Station (ATSS) that would be assembled in orbit about the year 2025.

A series of four NASA sponsored studies (References 1 through 4) provided the subsystem concepts and definitions of the technology requirements. The first two studies established the mission requirements and subsystem configurations focusing on the opportunities for synergy and necessary technical advances. The remaining studies included evaluation of orbital effects on large spacecraft which merged synergy into the necessary features of the configuration. For the ATSS the technology requirements included the development of the necessary synergies.

The mission requirements, subsystem concepts and technologies evaluated herein support a large, multipurpose space station which would provide an artificial gravity environment compatible with long-duration human occupancy. These studies also identify the need for, and assume the availability of, a heavy-lift launch vehicle capable of delivering a 270,000 kg (595,000 lb) payload to LEO which is more than double that of a Saturn V.

In the process of evaluating the ATSS configurations and options, a number of computer aided design tools were utilized. The IDEAS^2 design tool, described in Reference 5, provided a most effective means for evaluating configuration options. This automated approach quickly provided data for parameters such as orbital aerodynamic drag, orbit-induced torques, vehicle dynamics, and control authority requirements. This design tool eliminated manual estimates and iterations associated with a large, complex space system evaluated for alternate configurations and concepts within a set of subsystem operating capabilities. The graphics capability within IDEAS^2 proved particularly useful in generating the conceptual images needed to support other analyses; Figure 1-1 illustrates that capability.

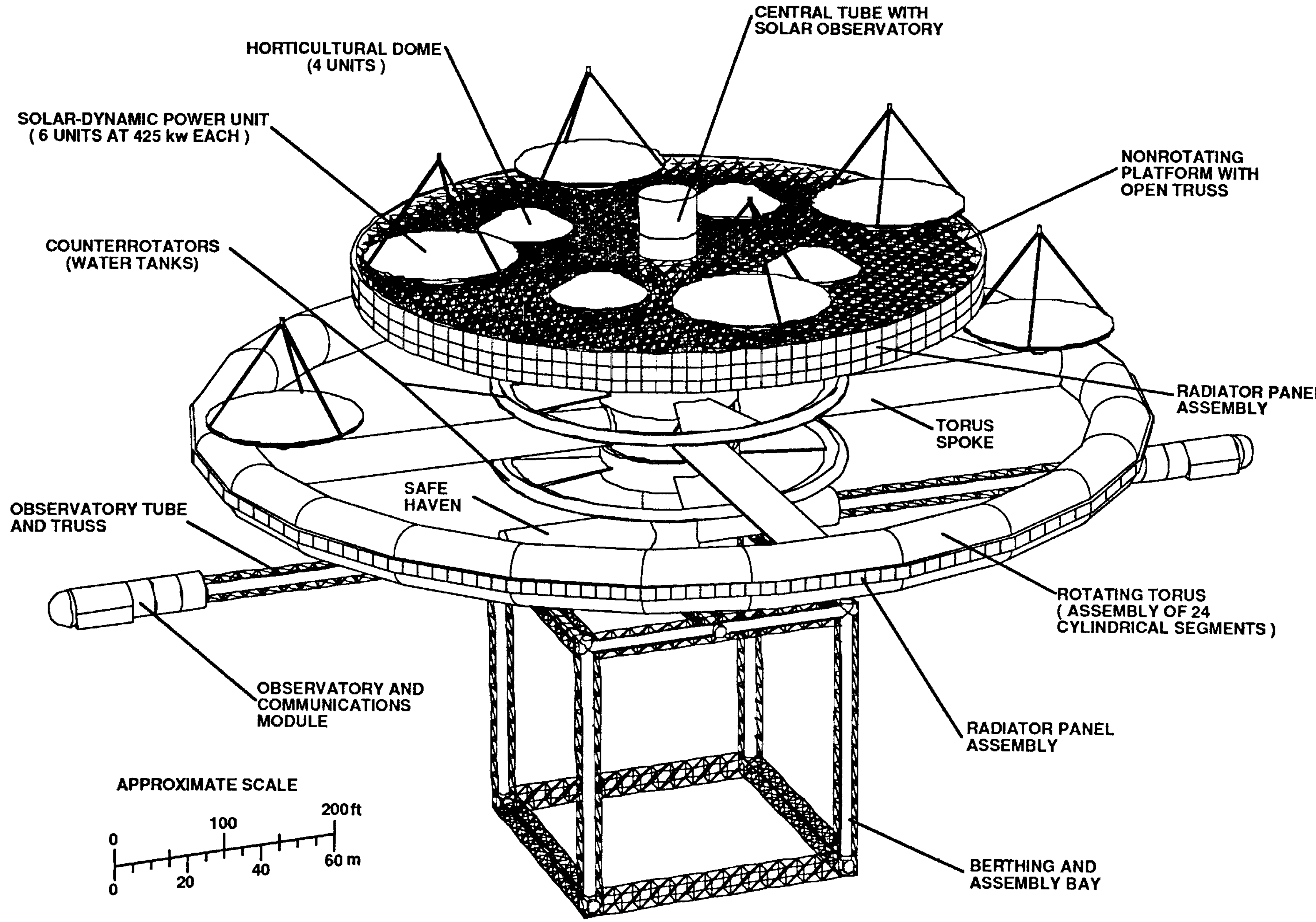


Figure 1-1 The Advanced Technology Space Station Concept Drawn Using the IDEAS² Computer Program

2.0 FUNCTIONAL REQUIREMENTS

The NASA contemporary planning literature such as References 6 and 7 provided the objectives and categories for future United States civil space initiatives. The broad functional requirements for the support of such missions were consolidated into a list of 17 items without regard for priority or ranking; Table 2-1 lists these functions in terms of four major support areas. An assessment of the implementation requirements for each of the functions led to estimates for the crew complement and the electrical-power demand. Table 2-2 summarizes these estimates for each of the major functional areas. Artificial gravity by rotation appeared as a general requirement for long-term human occupancy. Previous studies (Reference 8) listed a 0.1 g threshold limit for traction and, since in a rotating system, Coriolis forces will disorient humans; a 3 rpm limit for sustained rotation was established. A review of functional support requirements for other spacecraft either as assembly or service, showed that some of the interplanetary and lunar exploration missions would require large spacecraft. These large spacecraft established the dimensional requirements for the support and servicing features. Therefore, the functional requirements which established the ATSS configuration consisted of 17 items as listed in Table 2-1, the assessments of crew size and power requirements, the rotational effects, and a size which could support other large spacecraft in orbit.

TABLE 2-1. FUNCTIONS OF THE ADVANCED TECHNOLOGY SPACE STATION

<u>SCIENCE AND RESEARCH</u>
Observatory for Earth, Space and Solar Measurements and Research
Orbital Science Research Laboratory
Variable Gravity Research Facility
Horticultural Research Facility
Technology Demonstration Facility

<u>HABITATION AND MEDICAL</u>
Crew Life Support
Variable Gravity Adaptations for Spacecraft Crews
Transients Accommodation (Tourists)
Medical Care for Crews and Transients

<u>MANUFACTURING</u>
Component Manufacture and Spacecraft Assembly
Microgravity Processing

<u>OPERATION SUPPORT</u>
Spacecraft Service and Repair
Transportation Node, Retrieve-Resupply-Deploy Satellites
Communication Center and Relay Point
Control Center for other Spacecraft
Energy Collection and Relay
Storage and Supply Center

TABLE 2-2. ATSS PERSONNEL AND POWER REQUIREMENTS

MISSION SUPPORT FUNCTION	PERSONNEL	POWER
Science and Research	10	100 kW
Habitation and Medical	26	700 kW
Manufacturing	12	1500 kW
Operation Support	12	200 kW
Total	60	2500 kW

Note: Habitation and Medical Include Contingency

3.0 VEHICLE CONFIGURATION DESCRIPTION

The configuration for the ATSS is described in detail in Reference 2, however the major features are summarized below. Figure 1-1 presents a computer-drawn version of the concept. Relevant dimensions and masses for the elements of the ATSS are given in Figures 3-1 and 3-2, respectively.

The ATSS employs a large rotating torus that generates artificial gravity by centripetal acceleration and provides the primary habitation and working areas for the crew. The torus also provides volume for gas (O_2 and H_2) storage. The diameter of the torus ring is 15.2 m (50 ft). The radius of the torus is 114.3 m (375 ft) such that an equivalent lunar gravity (approximately one sixth Earth gravity) can be obtained at 1.14 rpm and an equivalent Earth gravity can by obtained at 2.8 rpm. The tolerable envelope for humans working in a rotating artificial-gravity environment is shown in Figure 3-3. The ATSS falls well within the limits and results in a gravity field that varies less than 10 percent throughout the torus and less than 2 percent over the body length of a crew member. Four cylindrical spokes connect the torus to a spherical hub. The spokes provide the access pathways to the torus in the form of freight and passenger elevators. In addition, two of the spokes have provisions for a variable-gravity facility. The hub contains the mechanisms for transfer, or exchange, between the rotating and nonrotating portion of the ATSS. The hub carries the rotating joints and seals at the central tube and also provides the running surfaces for the two counterrotators. The counterrotators are toroidially shaped water tanks with a 91.4 m (300 ft) outside diameter that null the angular momentum of the torus. This feature facilitates precession of the ATSS at the one-revolution-per-year rate required to maintain a Sun-facing attitude. For the purposes of this study, the counterrotation rate has been set at 10 rpm and this condition results in large estimates of the masses for the counterrotators and represents a major contribution to the total mass of the ATSS. The use of water is one of the

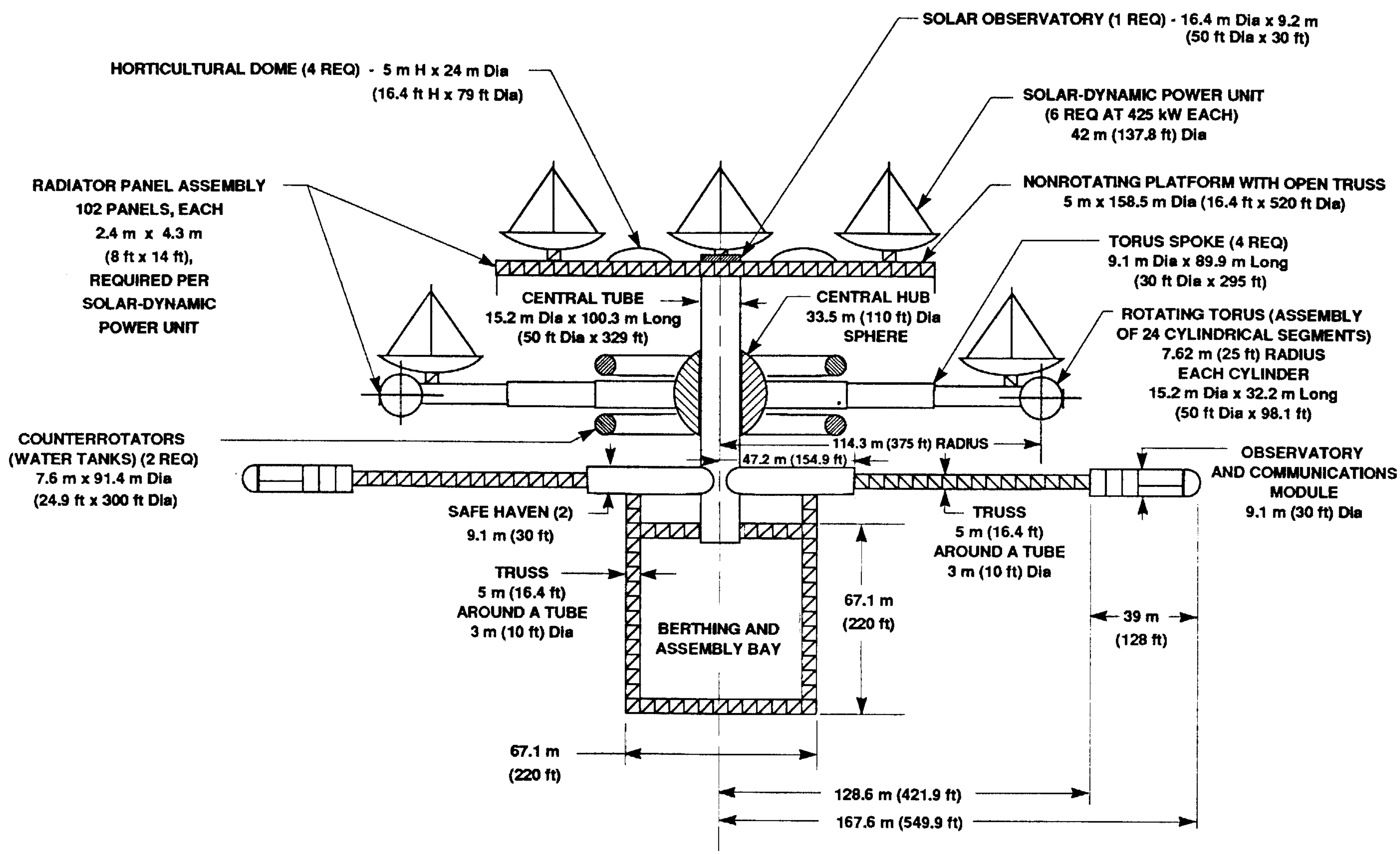


Figure 3-1 ATSS Summary of Principal Dimensions

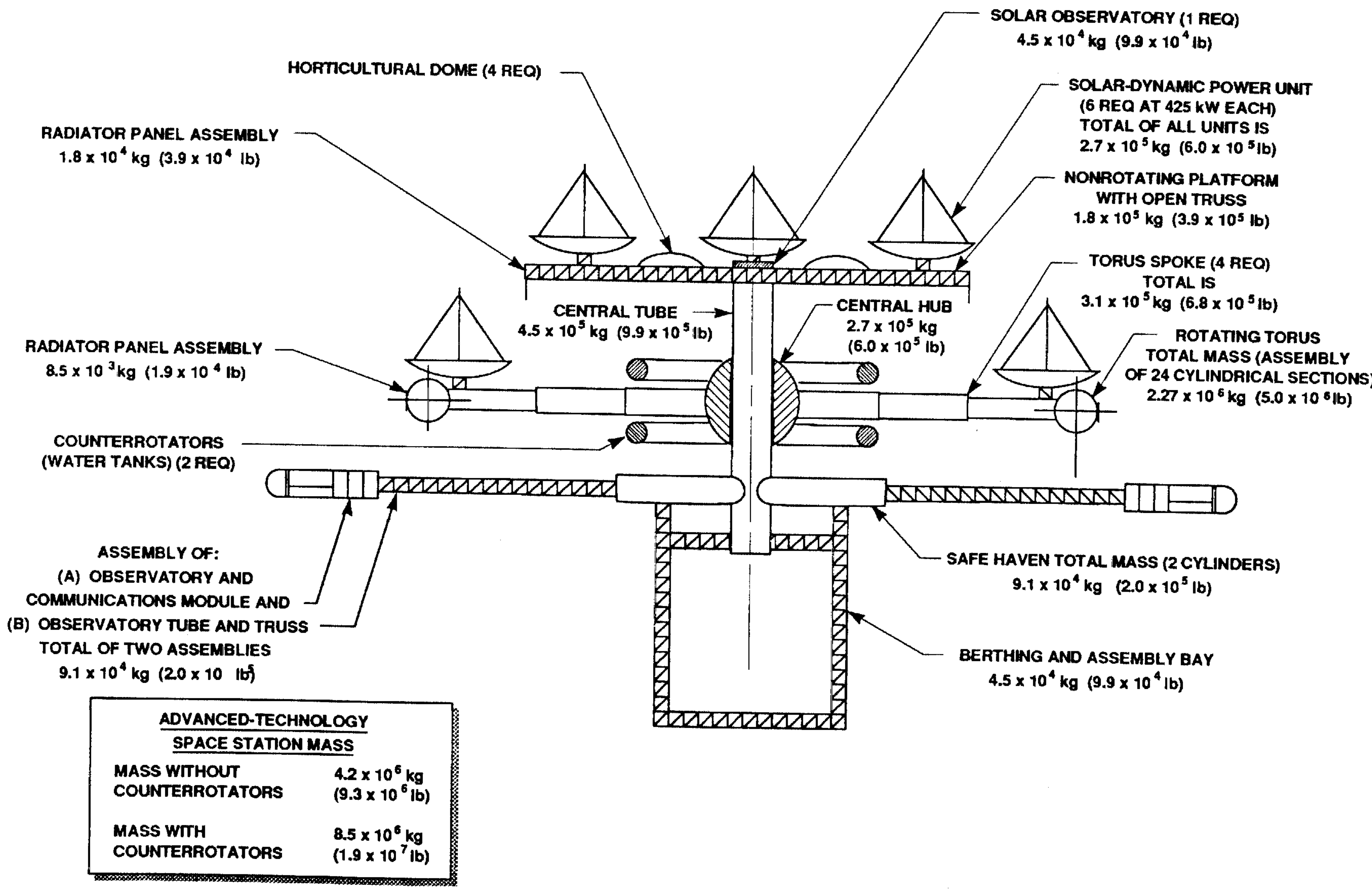


Figure 3-2 ATSS Summary of Principal Masses Assuming Space Station Freedom Technology

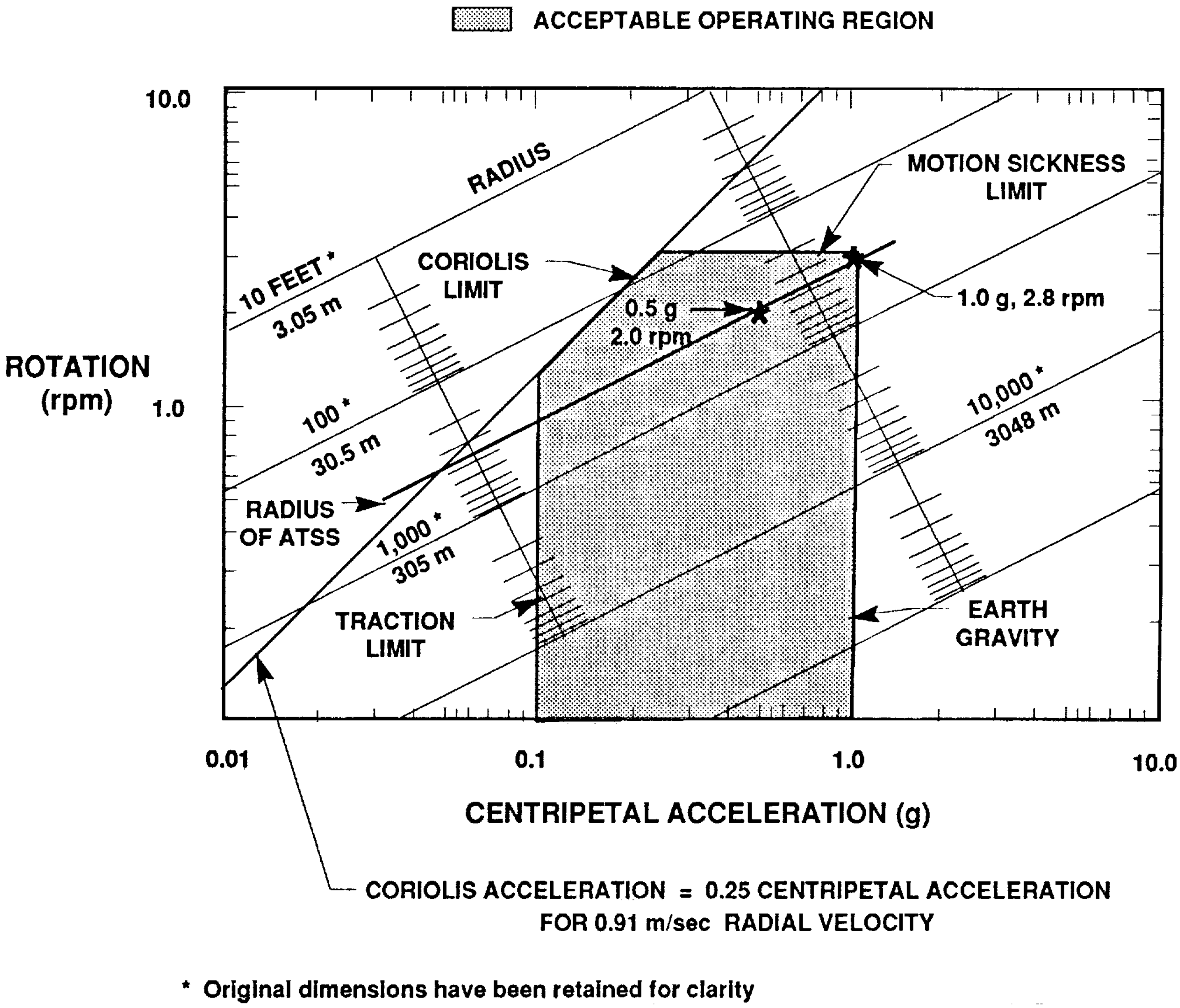


Figure 3-3 Human Operational Limits for Artificial Gravity by Rotation

principal synergies within the ATSS configuration. Water ballast, carried in the counterrotators, simultaneously performs the orbit-critical functions of nulling the angular momentum to permit sun-facing equilibrium and countering the gravity-gradient torques associated with a sun-facing orbital attitude. The water ballast also provides the reservoir that supplies crew usages and experiments before being electrolyzed to produce O_2 and H_2. These gases replenish the atmosphere, reduce CO_2, and become the propellants for station keeping. The ATSS has an extra capacity for electrolysis that makes H_2 and O_2 available for other uses such as propellants for an orbital-maneuvering vehicle.

A sun-facing, nonrotating central tube, illustrated in Figure 3-4, provides a common axis for the rotating elements, an access pathway within the ATSS and a point of attachment for all other elements. The central tube has a diameter of 15.2 m (50 ft) and a length of 100 m (328 ft). The sun-facing end provides a solar observatory. The remaining volume houses a microgravity facility and a number of bays separable by air locks for the assembly or servicing of other spacecraft. Transfer operations to the rotating portion of the ATSS utilize the two transfer ports. The main transfer port is concentric with the center line of the spokes and is intended for large objects serviced by the freight elevators. The personnel transfer port leads to a passenger elevator that moves along the outer wall of a spoke. The main air lock, at the end of the central tube, opens into a berthing bay. The bay consists of an open-faced cube with edges 67.1 m (220 ft) long formed by 3 m (10 ft) diameter tubes surrounded by 5 m (16.4 ft) bay trusses. The berthing bay accommodates supply flights and the assembly or servicing of large spacecraft by use of robotic booms and manipulators that move along the edges of the cube. The outboard ends of the tubes have air-lock ports which permit the docking of crew transfer vehicles such that crews and "carry on" items can be exchanged in a "shirtsleeve" environment.

The inboard ends of the berthing bay terminate in crew safe havens which are joined to the central tube and form the bases of the observation tube sections. These safe

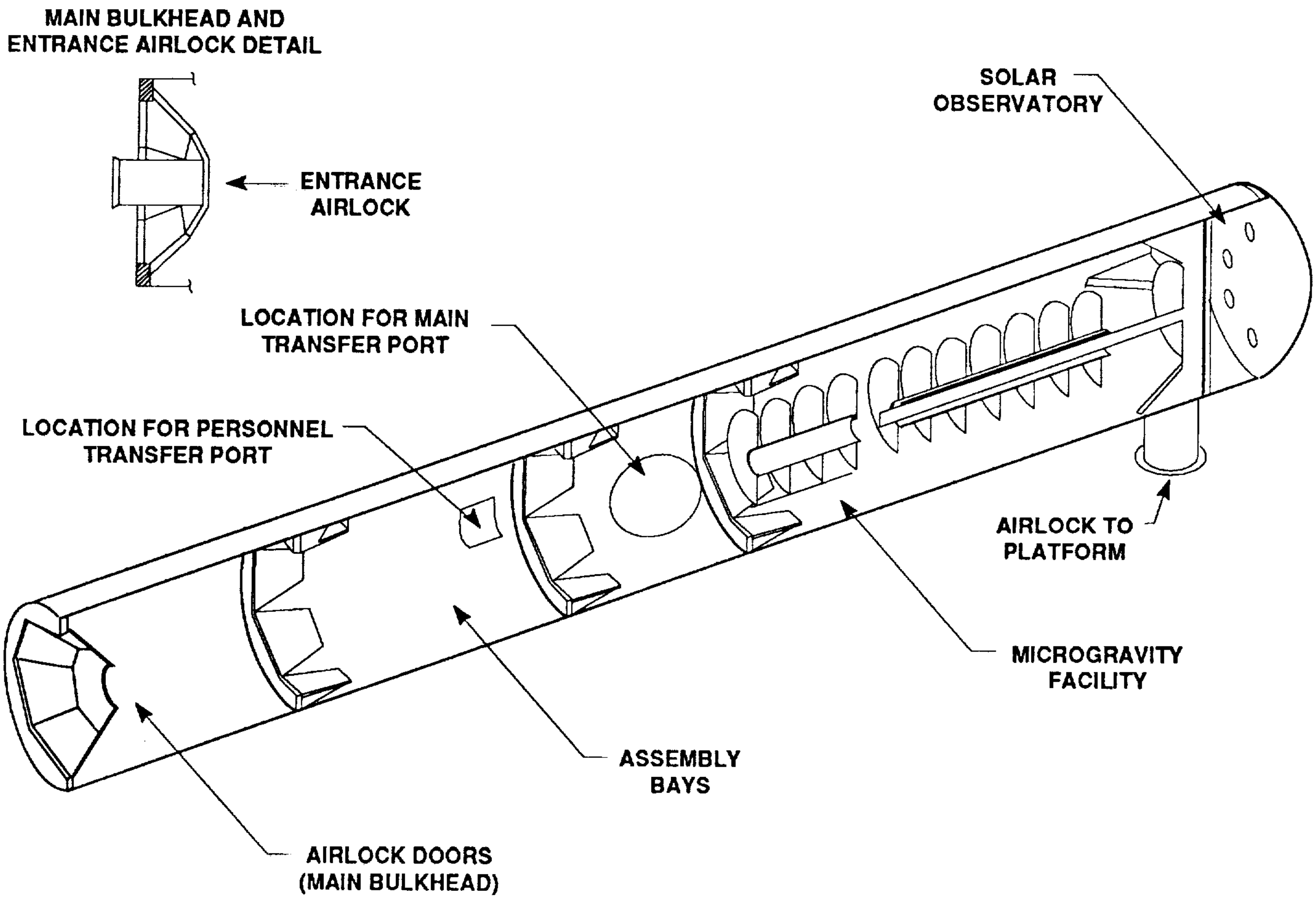


Figure 3-4 ATSS Central Tube, Principal Features

havens have a diameter of 9.1 m (30 ft) and a length of 39.6 m (130 ft). They provide temporary living facilities for crew members working in microgravity conditions and have the capability of supporting the entire crew should an emergency occur.

The observation tubes carry identical observatory and communication sections at each end, these are illustrated in Figure 3-5. The sections include a celestial observatory, and an Earth observatory, a communication section, a tracking section and an energy relay section. The end sections are 9.1 m (30 ft) in diameter and 39 m (128 ft) long. The incorporation of celestial -and Earth-viewing observatories requires the observation tube to be stabilized perpendicular to the plane of the ecliptic.

The sun-facing end of the central tube supports a platform 158.5 m (520 ft) in diameter constructed as an open truss of 5 m (16.4 ft) bays. The platform provides an area for mounting experiments and supports four domes for horticultural research.

Electrical power generation for the ATSS utilizes six identical solar-dynamic units; each generates 450 kW and delivers 425 kW continuously. Two of the units are mounted on the torus and the remaining four are mounted on the platform, such that the total installation distributes power throughout the ATSS and eases requirements for power transfer across rotating joints. The principal features of the solar-dynamic units are paraboloid-of-revolution concentrators 42 m (137.8 ft) in diameter feeding collectors at the focus. These collectors store energy in a molten salt phase change and thereby supply a continuous heat input to converters which transform 40 percent of the heat energy into electrical energy.

The internal configuration of the ATSS allows the crew to move about the entire station in a pressurized environment. Transfers between the rotating and nonrotating sections do not involve changes in the ambient atmosphere. The rotating torus provides the primary living and working areas. Figure 3-6 presents an overview of the torus and identifies the principal functional areas and the gas-storage volumes. The habitat sections at spokes 1 and 3 consist of three radial decks with crew quarters on the innermost deck,

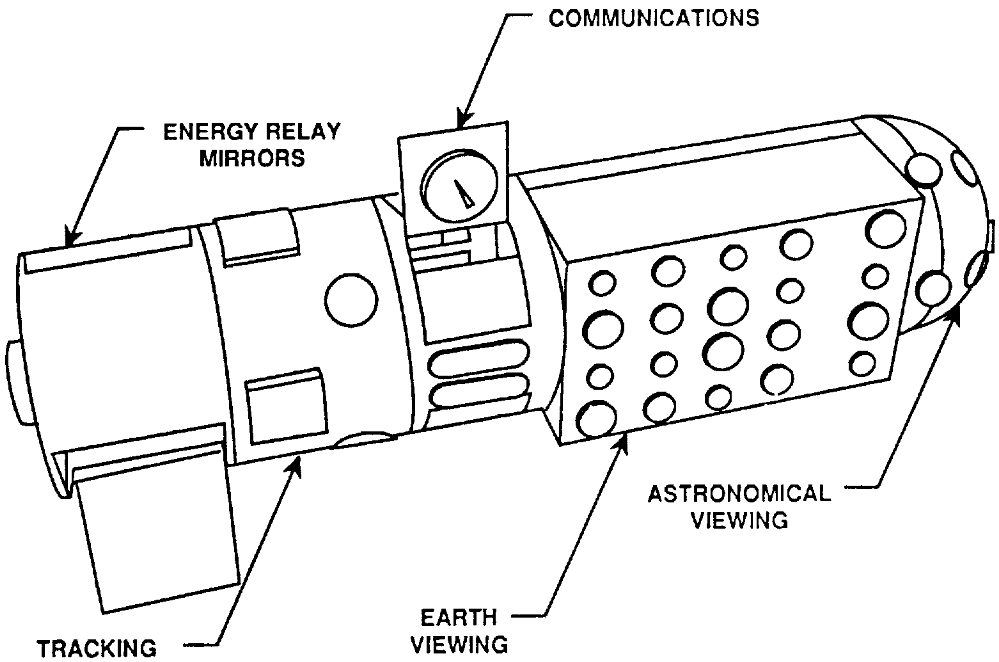


Figure 3-5 ATSS Observation Tube, End Sections

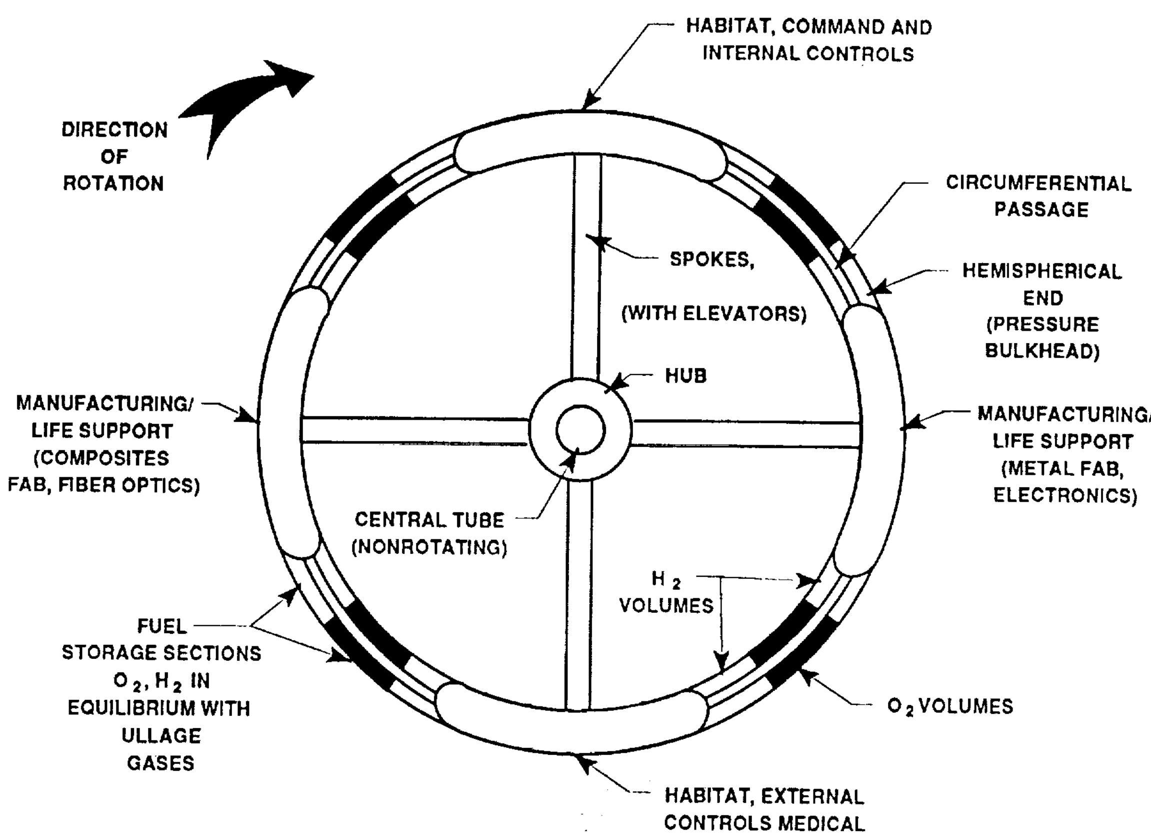


Figure 3-6 ATSS Rotating Torus, Summary of Sections and Principal Functions

command and control operations on the middle or "main" deck; and laboratories or storage areas in the outermost deck. Space between the decks and the torus shell provide passages and ducting for ventilation, water supplies, electrical leads, and data lines. In concept, the command and control functions at spoke 1 focus upon the activities performed within the ATSS and the control functions at spoke 3 focus upon communications and relay operations with other spacecraft and the Earth. Fabrication options selected for this study consisted of metal working, composites, electronics, and fiber optics. The areas at spokes 2 and 4 carry the fiber optics and electronics on partial inner decks whereas the metal working and composite forming are performed on the main deck in a high bay area. The outer decks carry duplicate installations of life-support equipment for the electrolysis of water, the reduction of CO_2, the oxidation of wastes, and the revitalization of the atmosphere. The remainder of the torus volume, about half, provides storage for the hydrogen and oxygen gases used for life support and as a station-keeping propellant. These gasses are stored separately and maintained at atmospheric equilibrium pressure by means of an "air bag" technique which is a derivation of dirigible technology. Oxygen or hydrogen contained within the bags are in pressure equilibrium with an external ullage gas. Ullage for oxygen is atmospheric air, however, ullage for hydrogen has to be inert; and could be either stored nitrogen, or CO_2 recovered from the cabin atmosphere. Each of the functions identified for the ATSS has a principal "performance" location. The functions and the areas within the ATSS where those functions are performed and supported are listed in Table 3-1.

The detail configuration for the ATSS was part of the initial study that focused upon the identification of technology requirements. In such a context, definitions for subsystems utilized one of two alternatives. If the advances in subsystem technology could be defined in terms of performance parameters, the current status was extrapolated to a goal for the year 2025. Such extrapolations apply particularly to communications and data handling where performance definitions are in terms of bit rates, operation rates,

TABLE 3-1. ATSS FUNCTIONS AND LOCATIONS FOR THEIR PERFORMANCE AND SUPPORT

FUNCTION	LOCATIONS WITHIN THE ATSS FOR PERFORMANCE AND SUPPORT
SCIENCE AND RESEARCH	
Observatory for Earth, Space, Solar Measurements and Research and Orbital Science Research Laboratory	Central Tube: Solar observatory (End only) instruments Observation Tube: Earth and space viewing instruments Platform: Experiment mountings Observation Tube: Experiment mountings Central Tube: Experiment mountings Torus: Central data processing
Variable Gravity Research Facility	Spokes: Facility location and service elevators Torus: Support, control, planning, and data processing
Horticulture Research	Platform: Solar facing domes, microgravity environment Spokes: Variable gravity under artificial light Torus: Control, planning, data processing
Technology Demonstration Facility	Platform: Exterior mounted items Central Tube: Microgravity items Spokes: Variable gravity items Torus: Control, planning, data reduction, parts and equipment fabrication
HABITATION AND MEDICAL	
Crew Life Support	Torus: General living, atmosphere revitalization Observation Tube: Short term living, safe haven for emergencies
Variable Gravity Adaptations	Spokes: Habitat and laboratory Torus: Life and technical support
Transients Accommodation (Tourists)	Torus: General living
Medical Care for Crews and Transients	Torus: Treatment and physical conditioning

TABLE 3-1. ATSS FUNCTIONS AND LOCATIONS FOR THEIR PERFORMANCE AND SUPPORT (concl.)

FUNCTION	LOCATIONS WITHIN THE ATSS FOR PERFORMANCE AND SUPPORT
MANUFACTURING	
Component Manufacturing Spacecraft Assembly	Torus: Parts fabrication and partial assembly operations Central Tube: Spacecraft assembly Berthing Area: Spacecraft final assembly Torus: Remote manipulator operation
Microgravity Processing	Central Tube: Microgravity facility Torus: System operation
OPERATION SUPPORT	
Spacecraft Service and Repair	Berthing Area: Spacecraft support Central Tube: Repair and assembly Torus: Parts fabrication, propellant generation, remote handling controls
Transportation Node, Retrieve-Fuel-Deploy	Berthing Area: Retrieve, fuel, deploy Observation Tubes: Tracking antennas for berthing and deploying Torus: Propellant generation, controls for berthing, handling and deployment
Communication Center and Relay Point	Torus: Control center for data acquisition recording and relay transmission Observation Tube: Antennas and laser telescopes for R.F. and optical links
Control Center for Other Spacecraft	Torus: Controls and mission planning support Observation Tube: Relay antennas for R.F. link, laser telescope for optical link
Energy Collection and Relay	Torus: Controls for propellant transfer and reflector operation, O_2/H_2 propellant generation Observation Tube: Deployable reflector for laser light beams
Storage and Supply Center	Central Tube: Ready storage Berthing Area: External storage Torus: Fabrication stock, technical supplies, food supplies, medical supplies

switching rates, etc. Within other subsystems, particularly structures, a number of advanced concepts could apply; the criteria for evaluation became the relative reduction of mass or relative improvements in stability or life. For such subsystems the initial definition for the ATSS is based upon the technology as used by Space Station Freedom with an intent to show the potential for improvement. Therefore, the initial summary of masses for elements of the ATSS represent estimates of structure and equipment based on present aluminum technology. The ATSS configuration assumes operation at an artificial-gravity level equal to that at the Earth's surface and with an internal atmospheric pressure equal to sea-level ambient.

4.0 HUMAN FACTORS CONSIDERATIONS

The long-term flight accommodations for humans aboard the ATSS must address two principal considerations: artificial gravity produced by rotation is necessary in order to inhibit degradations within human musculoskeletal and cardiovascular systems; the internal atmosphere within the ATSS must satisfy human breathing requirements for oxygen content and freedom from contaminants. Both considerations have significant impact upon the structural concepts for the ATSS; and in addition the effects of the rotation rate extend into the requirements for attitude control and propulsion.

4.1 Artificial Gravity by Rotation

The principal physiological effects of living in a reduced-gravity environment are losses of bone calcium and losses of muscular tone due to reduced loads accompanied by a reduction in blood volume due to a lowered hydrostatic pressure. To date, all humans in orbit have flown in a microgravity "weightless" environment and countered the resulting physiological effects through physical preconditioning, drug therapy, special clothing, and in-flight exercise regimens. All long duration flights to date have shown an ever increasing requirement for conditioning exercise at the expense of production time, and a continuing loss of bone calcium. Artificial gravity by rotation will provide relief from these effects. So far, only very limited data exists for levels less than 1 Earth gravity. Artificial gravity by rotation introduces Coriolis accelerations and these have potentially disorienting effects on humans. The most severe disorienting effect occurs when the brain receives visual signals that differ from the vestibular system signals. Humans adapt quickly to the other Coriolis effects felt as side forces or limb heaviness. Coriolis effects and rotation limits have been defined for humans, and these limits define the operating boundaries for artificial gravity by rotation. Figure 3-3 identifies those limits and shows the operating regime in terms of rotation rate, gravity equivalent, and radius. The radius selected for the ATSS, 114.3 m (375 ft), permits operation over the full range of partial gravity without exceeding the rotation limit. Additionally, the radius shows a significant margin relative to Coriolis concerns.

For the purposes of this study, the ATSS was assumed to operate at a rotation rate that produced an Earth equivalent gravity at the center of the torus. Crew operations within the torus would be free from any gravitationally induced physiological effects. The rotating environment however, produces some sensory conflicts arising from the differences between vestibular and visual signals. The configuration details of the torus minimize such conflicts and include features such as placement of control panels in a manner to make the operator face into the direction of motion, and locating sleeping quarters such that the body axis remains parallel to the axis of rotation. Crew accommodations address long-term occupancy in a manner analogous to a small cruise ship with a galley to prepare food, a dining area, and comfort provisions that include showers, laundry facilities and medical services.

4.2 Atmospheric Pressure and Control

The early U.S. space flights utilized a variety of breathing atmospheres in response to constraints of mass, leakage, or compatibility with space suits for extravehicular activity (EVA). All of the atmospheres maintained the O_2 partial pressure at an Earth sea-level equivalent within the lungs of the crew. The Shuttle nominally operates with an internal atmosphere content and pressure equivalent to Earth sea-level standard. The pressure limitations of present space suits require a long prebreathe sequence to accommodate EVA. Space Station Freedom will operate with an internal atmosphere equivalent to Earth sea-level standard; the new higher pressure space suits will eliminate the prebreathe requirement. The atmosphere for the ATSS has also been selected at Earth sea-level standard conditions although operation is equally feasible over a range of reduced pressures. In addition, operation at lower internal pressure eases some structural requirements.

Reducing the pressure in a breathing atmosphere is generally accomplished by reducing the nitrogen content of the atmosphere. Operation with a reduced nitrogen content results in a corresponding decrease in the nitrogen loss from leakage and thereby eases the makeup requirements. There is a practical limit to pressure reduction at an atmospheric content of about 30 percent oxygen at which many of the general use materials become combustible. ATSS studies have not considered operation with atmospheres containing more than 30 percent oxygen.

5.0 ATSS STRUCTURES

The ATSS will utilize advanced structural concepts that include preassembled modules, expandable telescopic elements, and erectable truss structures all delivered to orbit on successive launches. The final assembly of the ATSS in orbit will use the combined capabilities of orbital maneuvering vehicles, mobile remote manipulator systems, and a telerobotic truss assembler. The EVA demand for the astronauts would be minimized by the use of telerobotic and knowledged-based machines to perform the final assembly and the required operational verifications.

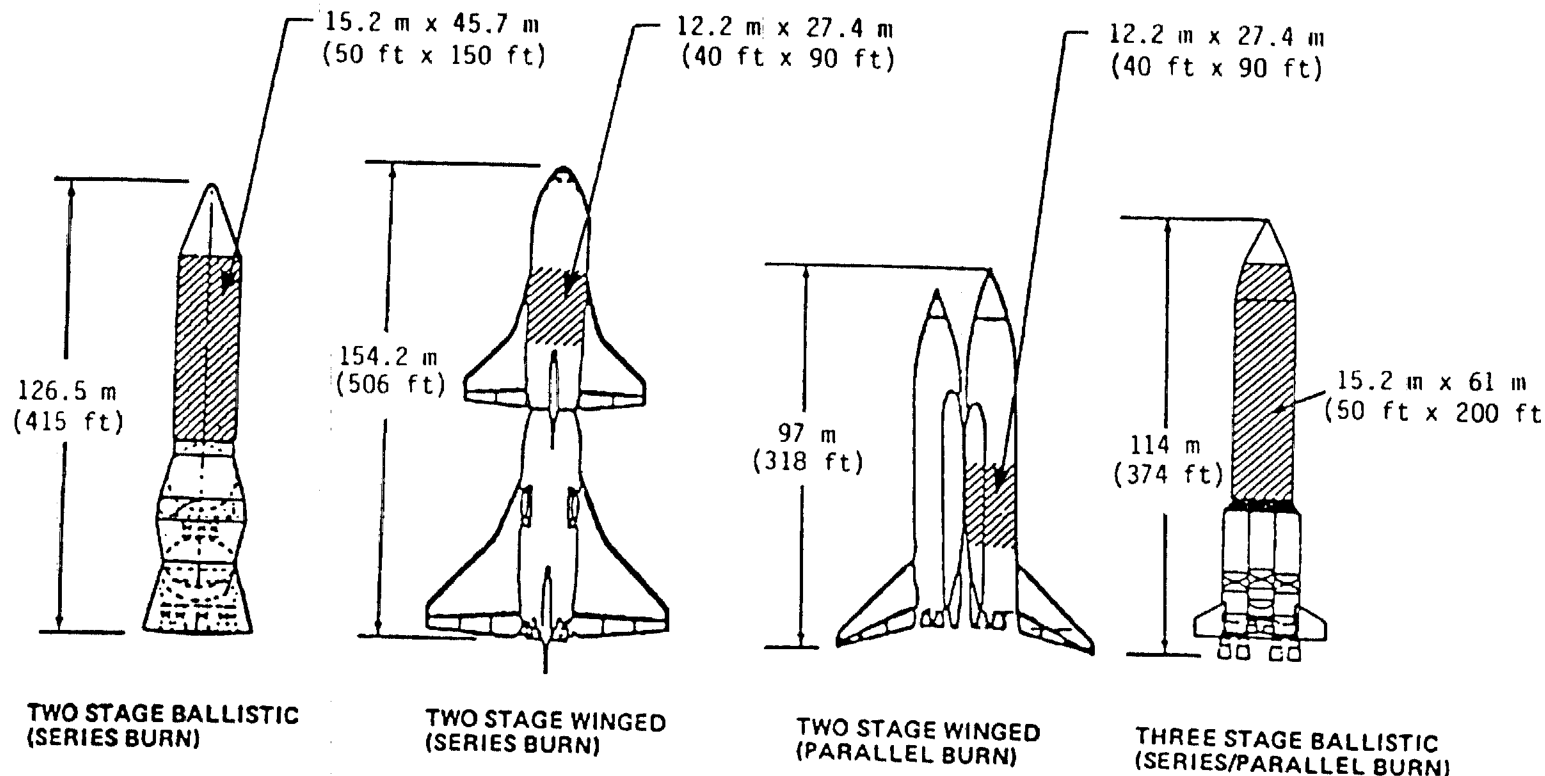
5.1 Transportation Infrastructure

The final assembly of the ATSS in LEO assumes the following transportation capabilities and infrastructure.

A. Heavy lift launch vehicles (HLLV): The ATSS requires the capability to handle payloads having masses up to 2.7×10^5 kg (6×10^5 lb). The launch vehicles will need the capability for delivering the 24 torus subassemblies of the ATSS to LEO in 12 launches. The payload envelope size and particular mass limitations for the HLLV will define the number and size of the modules and subassemblies. Four examples of HLLV concepts are shown in Figure 5-1 for comparison of cargo sizes (Reference 9).

B. A passenger-and-cargo transport vehicle, such as Shuttle II: The transport vehicle will deliver and return 20 persons from LEO. The Shuttle II will be fully recoverable using a flyable booster and spacecraft as shown in Figure 5-2 (Reference 10).

C. A "smart" orbital maneuvering vehicle (OMV): A typical unit is shown in Figure 5-3. The OMV operates as a space tug to maneuver massive structures into position for final assembly. In addition, the OMV could be outfitted with different end effectors that can grapple spacecraft, operate



(Shaded Area Shows Payload Volume)

Figure 5-1 Concepts for Heavy Lift Launch Vehicles Capable of Delivering 270,000 kg (595,000 lb) to LEO

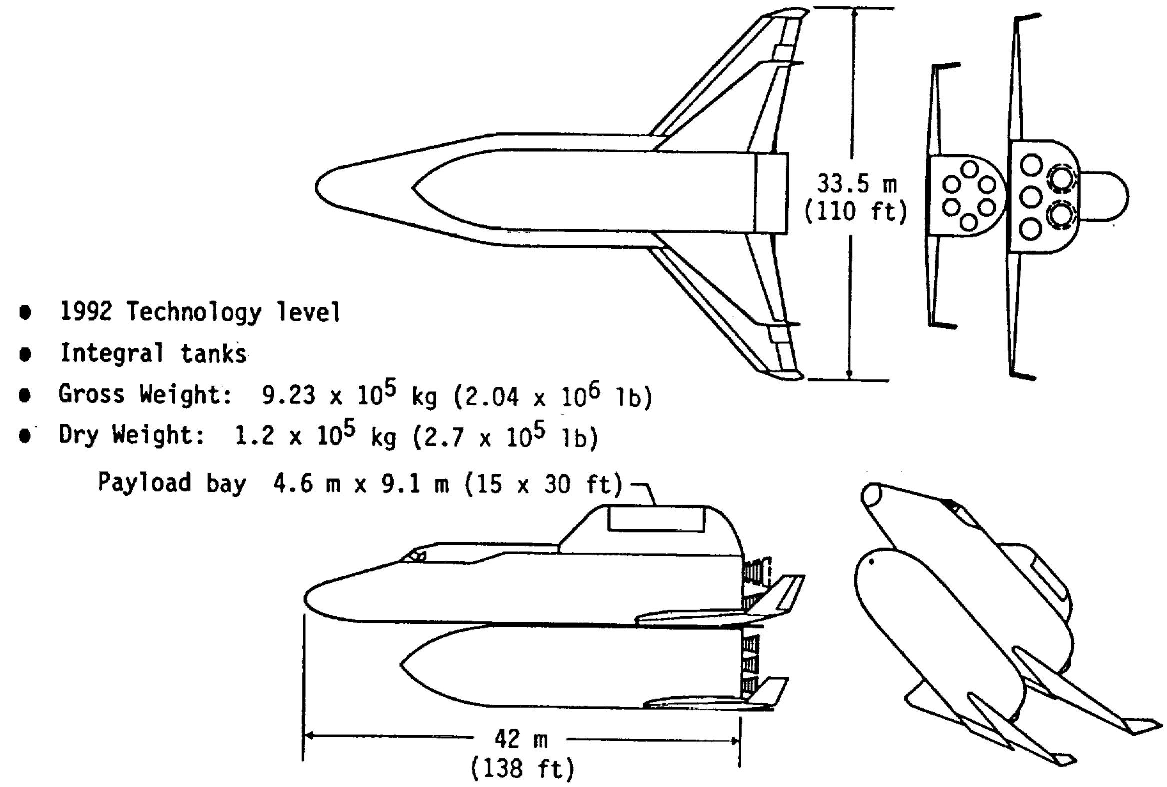


Figure 5-2, Concept for Shuttle II, Advanced Cargo and Personnel Transporter.

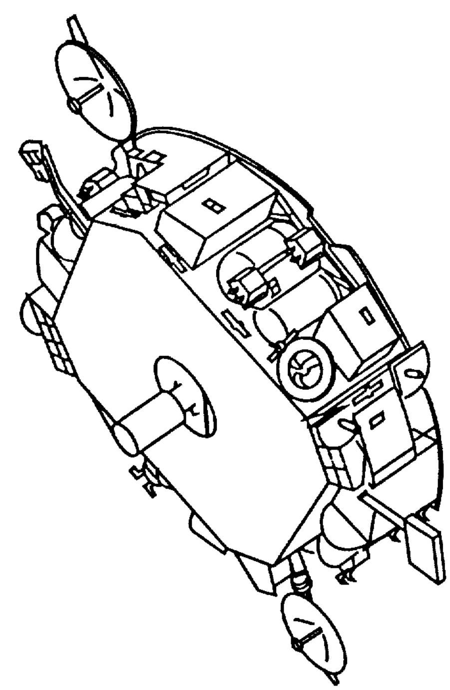


Figure 5-3, Concept for an Orbital Maneuvering Vehicle.

levers, rotate mechanical fasteners, or actuate cam-lock attachments (References 11 and 12).

D. A telerobotic truss assembler: The unit would consist of a mobile base that carries a remote manipulator. This "smart" system would recognize bar codes on structural elements and assemble the parts into predetermined configurations. Experiment packages could also be positioned and attached to the truss structure. A concept for a robotic assembler attached to a mobile remote manipulator system ((MRMS) is shown in Figure 5-4. (Reference 13).

E. Telerobotic functional units: A conceptual unit is shown in Figure 5-5 (From Reference 14). The unit is refueling a spacecraft in LEO while attached to a remote manipulator arm (RMA) of the Shuttle. The ATSS would carry similar units that would operate from the platform or from the observatory truss structure during assembly. These items would move to the berthing bay for continuing use.

F. An orbital-transfer vehicle (OTV): The OTV has the capability to service or retrieve satellites from geostationary orbits (GEO) and beyond. An example of an aerobraked OTV oxygen tanker is shown in Figure 5-6 (Reference 15).

5.2 Expandable Structures

The design of the ATSS utilizes two examples of expandable structural concepts. These concepts offer the advantage of high packaging density within the payload bay of the available HLLV. The two examples considered in the design of the ATSS are the cylindrical telescopic torus spokes and the in-orbit assembled truss structure shown in Figures 5-7 and 5-8 (Reference 2).

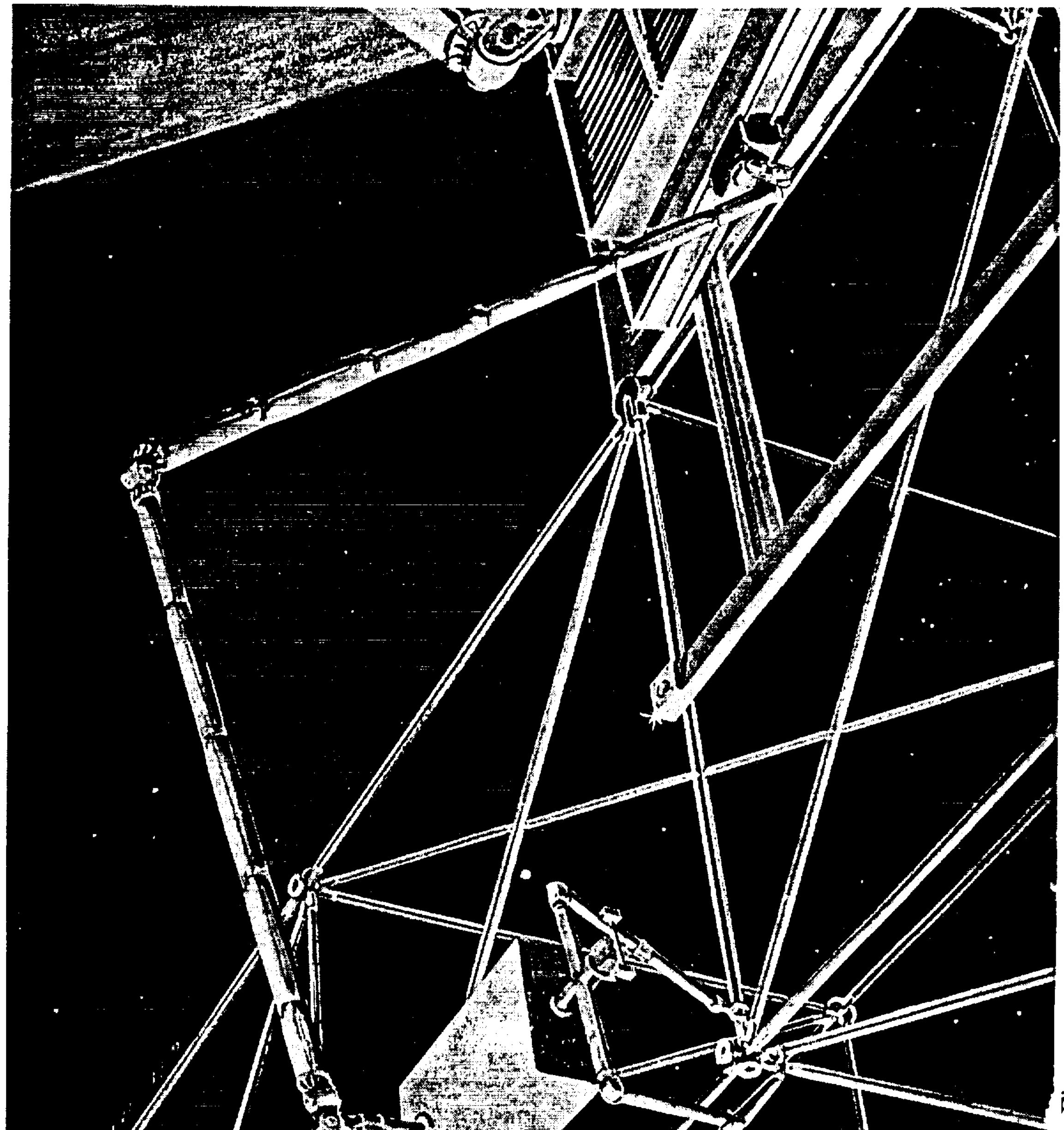


Figure 5-4, Concept for a Remote Robotic Truss Assembler.

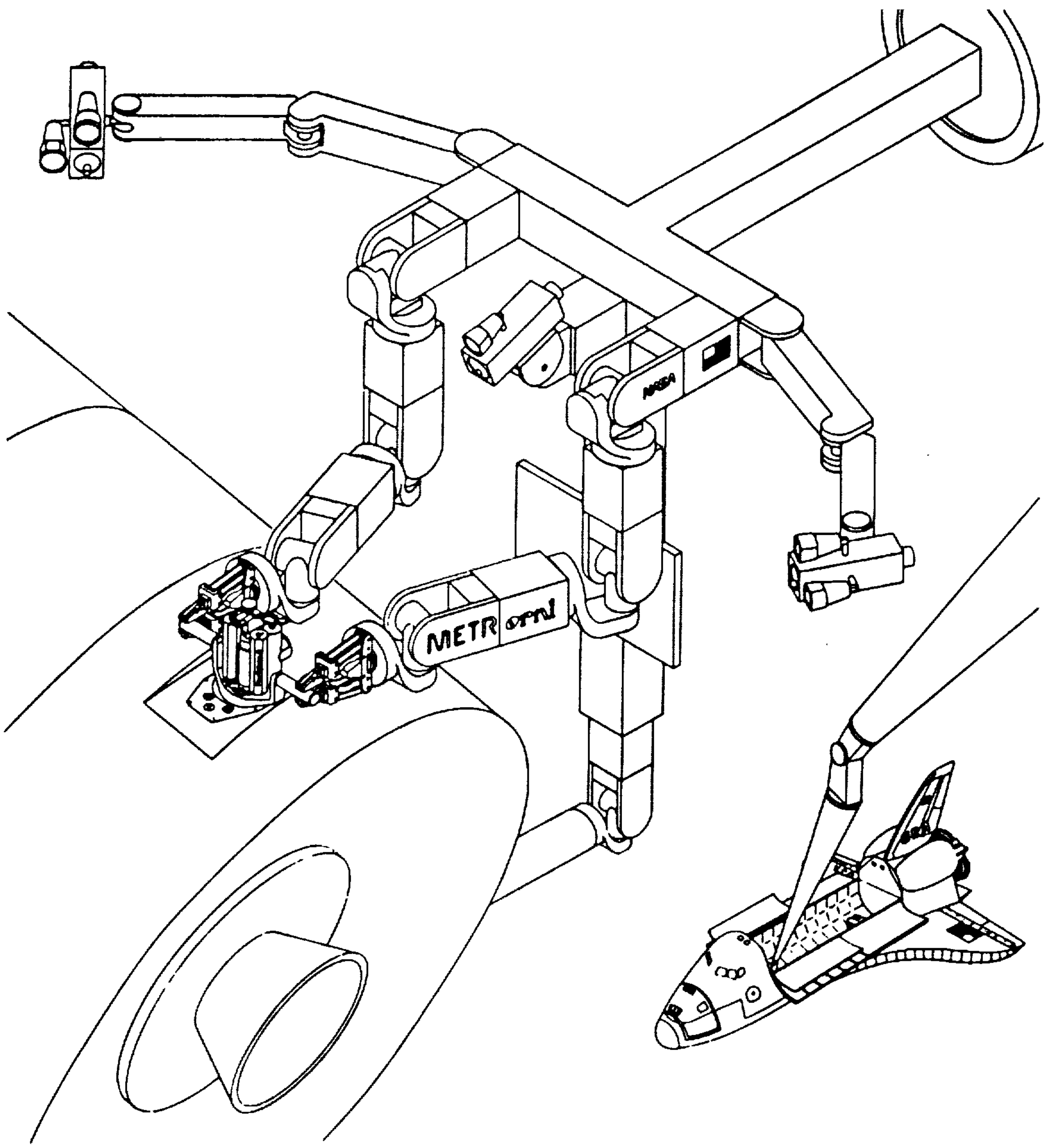


Figure 5-5, Concept for a Telerobotic Assembler.

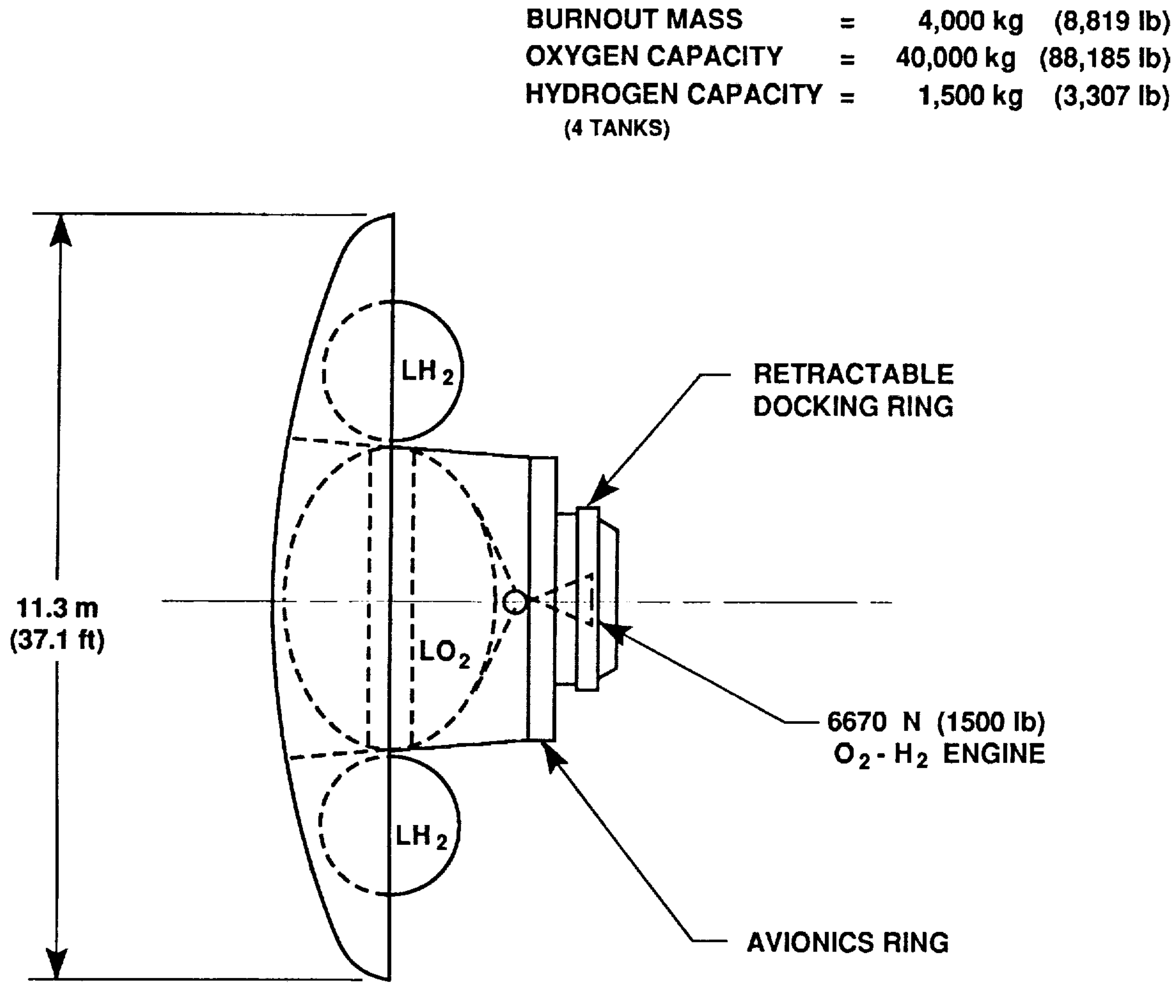


Figure 5-6, Proposed Configuration for an Orbital Transfer Vehicle.

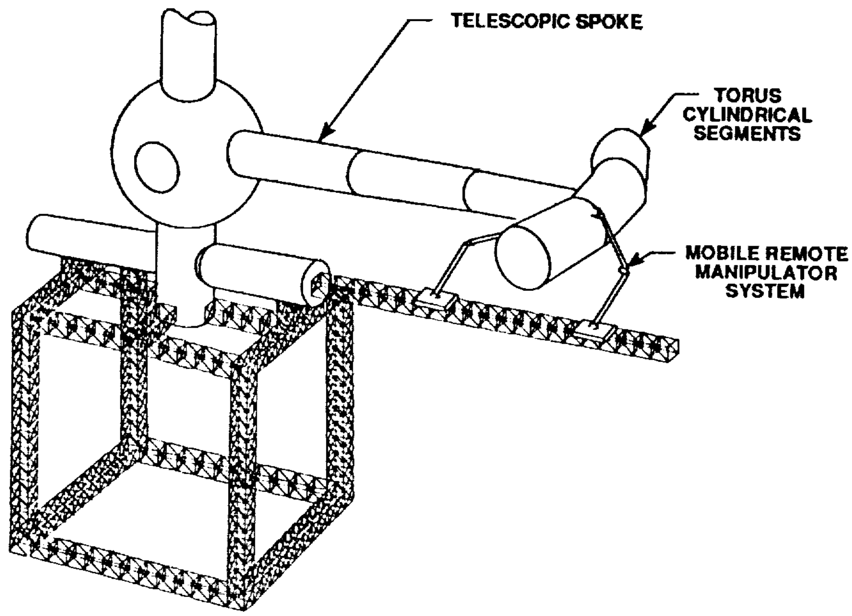


Figure 5-7, In-Orbit Assembly of the ATSS Truss and Telescoping Spokes.

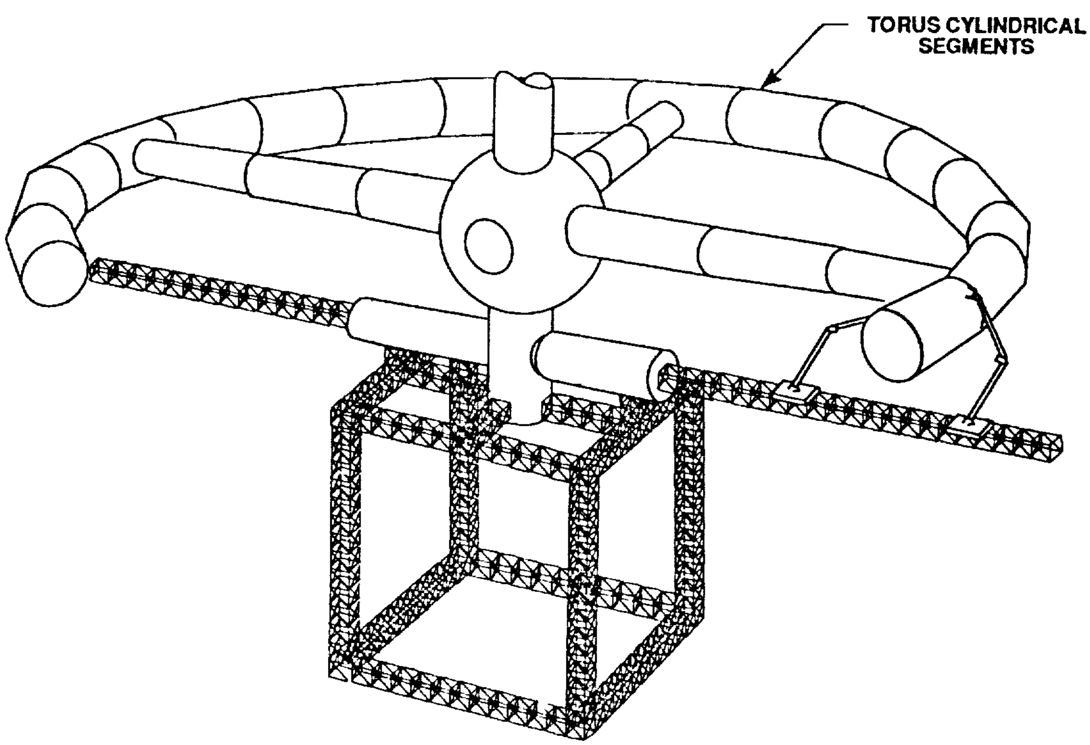


Figure 5-8, In-Orbit Assembly of the ATSS Torus Sections.

A. The cylindrical spokes of the torus are 9.1 m (30 ft) in diameter by 89.9 m (295 ft) in length when assembled to the torus in orbit. The structure of the spokes is designed for telescoping into a cylinder with an overall length of 30 m (98.4 ft), which allows delivery of two torus spokes with one HLLV launch. At final assembly in orbit, the spokes are extended and made rigid by metal-to-metal structural joints.

B. The orthogonal tetrahedral truss structure is an assembly of identical cubic bays each 5 m (16.4 ft) on a side. The ATSS truss structures planned for assembly in orbit are the platform, the external support for the berthing and assembly bay tubes and the external support for the observatory tubes. The telerobotic truss assembler performs all of the joining and locking operations.

5.3 ATSS Assembly Sequence

The in-orbit assembly sequence begins with a series of maximum envelope HLLV flights that deliver the central tube and the rotating hub. Table 5-1 summarizes the assembly steps up to the point for installation of the counterrotators. The table includes the HLLV launches with the payload and estimates of mass and identifies the supporting launch requirements for the assembly crews. The interactions of supporting equipment with elements of the ATSS during assembly are illustrated in Figure 5-9.

The sequence begins with all operations using gravity gradient stabilization. The shift into a Sun-facing attitude coincides with the availability of electrical power and a stabilization capability to counteract the cyclic forces imposed by gravity-gradient torques.

The assembly of the inhabited sections require 25 HLLVs to place the ATSS subassemblies in LEO. The HLLVs will be launched at a rate of approximately one per month. HLLV payloads will include assembly aids such as the mobile remote manipulators and the telerobotic truss assemblers. The assembly team will be transported to and from the assembly orbit in a 20-passenger shuttle. OMVs will be delivered on two

TABLE 5-1. ATSS IN-ORBIT ASSEMBLY SEQUENCE

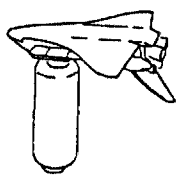
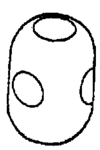
ASSEMBLY SEQUENCE	HLLV LAUNCHES	SHUTTLE LAUNCHES	PAYLOAD DESCRIPTION	PAYLOAD SIZE AND WEIGHT	CUMULATIVE MASS PROPERTIES	EVA AND ASSEMBLY AID REQUIREMENTS
	1	0	CENTRAL TUBE HABITAT 1	15.2 m Dia x 30.5 m (50 ft Dia x 100 ft) 2.27 x 10^5 kg (5 x 10^5 lb)	2.27 x 10^5 kg (5 x 10^5 lb)	NONE
	0	1	ASSEMBLY CREW BOARDS HABITAT I 1 ORBITAL MANEUVERING VEHICLE (OMV) DOCKED TO EXTERIOR	20 PERSONS OMV 9.9 x 10^3 kg (2.2 x 10^4 lb)	2.4 x 10^5 kg (5.2 x 10^5 lb)	NONE
	1	0	HUB OF CENTRAL TUBE	33.5 m Dia x 30.5 m (110 ft Dia x 100 ft) 2.72 x 10^5 kg (6 x 10^5 lb)	5.09 x 10^5 kg (1.1 x 10^6 lb)	NONE
	1	0	CENTRAL TUBE HABITAT II	15.2 m Dia x 30.5 m (50 ft Dia x 100 ft) 2.27 x 10^5 kg (5 x 10^5 lb)	7.4 x 10^5 kg (1.6 x 10^6 lb)	NONE

TABLE 5-1. ATSS IN-ORBIT ASSEMBLY SEQUENCE (Continued)

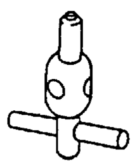
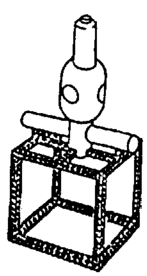
ASSEMBLY SEQUENCE	HLLV LAUNCHES	SHUTTLE LAUNCHES	PAYLOAD DESCRIPTION	PAYLOAD SIZE AND WEIGHT	CUMULATIVE MASS PROPERTIES	EVA AND ASSEMBLY AID REQUIREMENTS
	0	0	CENTRAL TUBE ASSEMBLY OPERATIONS	–	7.4×10^5 kg (1.6×10^6 lb)	LIMITED USE OF EVA FOR INSTALLATION OF FASTENERS EXTENSIVE USE OF OMV TO POSITION HUB AND HABITAT II FOR ASSEMBLY
CREW CHANGEOVER	0	1	ASSEMBLY TEAM OMV DOCKED TO HABITAT I EXTERIOR	20 PERSONS OMV 9.9×10^3 kg (2.2×10^4 lb)	7.48×10^5 kg (1.65×10^6 lb)	NONE
	1	0	TWO SAFE HAVEN MODULES	EACH MODULE SIZE 9.1 m Dia x 39.6 m (30 ft Dia x 130 ft) TOTAL WEIGHT OF TWO MODULES 9.1×10^4 kg (2×10^5 lb)	8.39×10^5 kg (1.85×10^6 lb)	EVA/IVA USED TO ASSEMBLE SAFE HAVENS USING OMV AS AN ASSEMBLY AID
	1	0	BERTHING AND ASSEMBLY BAY	TRUSS ELEMENTS FOR BERTHING BAY, OBSERVATORY BOOMS, PLATFORM AND TELEROBOTIC TRUSS ASSEMBLER 9.1 m Dia x 39.6 m (30 ft Dia x 130 ft) 2.27×10^5 kg (5×10^5 lb)	1.07×10^6 kg (2.36×10^6 lb)	EVA/IVA PLUS OMV AND TELEROBOTIC TRUSS ASSEMBLER USED TO ASSEMBLE THE BAY

TABLE 5-1. ATSS IN-ORBIT ASSEMBLY SEQUENCE (Continued)

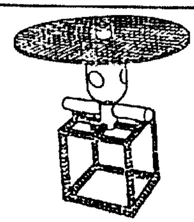
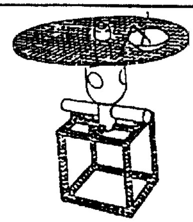
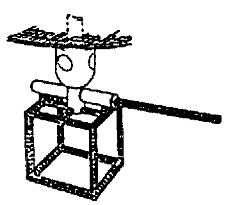
ASSEMBLY SEQUENCE	HLLV LAUNCHES	SHUTTLE LAUNCHES	PAYLOAD DESCRIPTION	PAYLOAD SIZE AND WEIGHT	CUMULATIVE MASS PROPERTIES	EVA AND ASSEMBLY AID REQUIREMENTS
	0	0	PLATFORM ASSEMBLY	–	1.07×10^6 kg (2.36×10^6 lb)	LIMITED EVA WITH EXTENSIVE USE OF TELEROBOTIC TRUSS ASSEMBLER AND OMV's
CREW CHANGEOVER	0	1	ASSEMBLY TEAM	20 PERSONS 2.3×10^3 kg (5×10^3 lb)	1.07×10^6 kg (2.36×10^6 lb)	NONE
	1	0	TWO 25 kW SOLAR DYNAMIC UNITS TWO MOBILE REMOTE MANIPULATOR SYSTEMS (MRMS)	9.1 m Dia x 24.4 m (30 ft Dia x 80 ft) 4.5×10^4 kg (9.9×10^4 lb)	1.11×10^6 kg (2.5×10^6 lb)	LIMITED EVA WITH EXTENSIVE USE OF MRMS's AND OMV's
	0	0	OBSERVATION BOOM ASSEMBLY	–	1.11×10^6 kg (2.5×10^6 lb)	LIMITED EVA WITH EXTENSIVE USE OF TELEROBOTIC TRUSS ASSEMBLER AND OMV

TABLE 5-1. ATSS IN-ORBIT ASSEMBLY SEQUENCE (Continued)

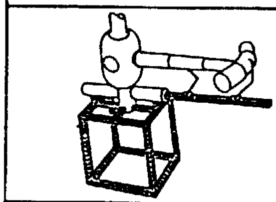
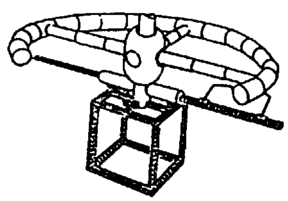
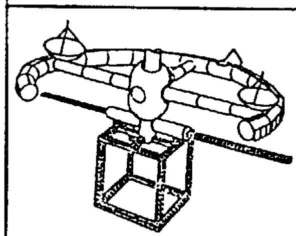
ASSEMBLY SEQUENCE	HLLV LAUNCHES	SHUTTLE LAUNCHES	PAYLOAD DESCRIPTION	PAYLOAD SIZE AND WEIGHT	CUMULATIVE MASS PROPERTIES	EVA AND ASSEMBLY AID REQUIREMENTS
	1	0	TWO TELESCOPIC SPOKES TWO MOBILE REMOTE MANIPULATOR SYSTEMS	9.1 m Dia x 61 m (30 ft Dia x 200 ft)	1.29×10^6 kg (2.85×10^6 lb) 1.82×10^5 kg (4×10^5 lb)	EXTENSIVE EVA/IVA AND MRMS's USED WITH THE OMV's TO MANEUVER THE SPOKES
CREW CHANGEOVER	0	1	ASSEMBLY TEAM	20 PERSONS 2.3×10^3 kg (5×10^3 lb)	1.29×10^6 kg (2.85×10^6 lb)	NONE
	1	0	TWO SPOKES AND TWO MRMS's	9.1 m Dia x 61 m (30 ft Dia x 200 ft) 1.82×10^5 kg (4×10^5 lb)	1.47×10^6 kg (3.24×10^6 lb)	EXTENSIVE EVA/IVA AND MRMS's USED WITH THE OMV's TO MANEUVER THE SPOKES AND TORUS SECTIONS FOR ASSEMBLY
			TWO TORUS SECTIONS PER LAUNCH	15.2 m Dia x 61 m (50 ft Dia x 200 ft) 1.82×10^5 kg (4×10^5 lb)	3.63×10^6 kg (8×10^6 lb)	
CREW CHANGEOVER	0	4	ASSEMBLY TEAM	20 PERSONS 2.3×10^3 kg (5×10^3 lb)	3.63×10^6 kg (8×10^6 lb)	NONE
	1	0	RADIATOR PANELS, MOBILE REMOTE MANIPULATOR SYSTEM WITH SUPPORT RAIL SYSTEM AND TWO SOLAR DYNAMIC UNITS	15.2 m Dia x 45.7 m (50 ft Dia x 150 ft) 9.1×10^4 kg (2×10^5 lb)	3.72×10^6 kg (8.2×10^6 lb)	EXTENSIVE EVA/IVA AND MRMS's USED WITH THE OMV's TO MANEUVER THE SOLAR DYNAMIC UNIT SUBASSEMBLIES

TABLE 5-1. ATSS IN-ORBIT ASSEMBLY SEQUENCE (Continued)

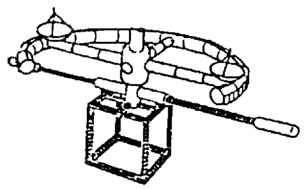
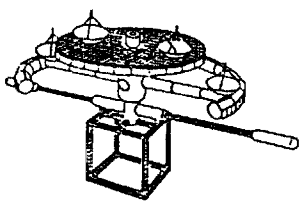
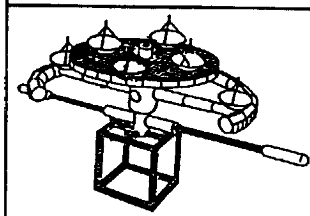
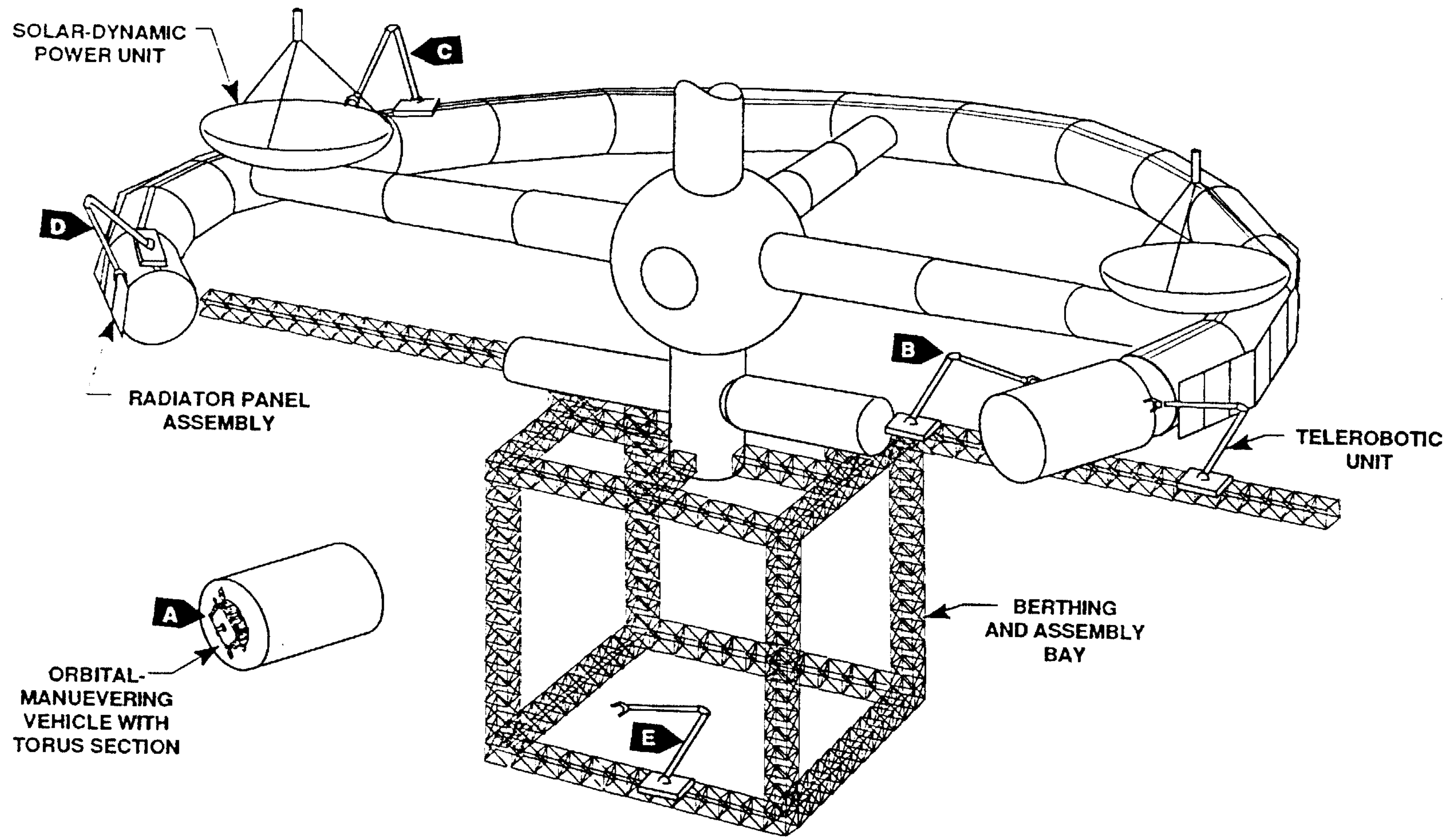
ASSEMBLY SEQUENCE	HLLV LAUNCHES	SHUTTLE LAUNCHES	PAYLOAD DESCRIPTION	PAYLOAD SIZE AND WEIGHT	CUMULATIVE MASS PROPERTIES	EVA AND ASSEMBLY AID REQUIREMENTS
	2	0	CELESTIAL OBSERVATORY INSTALLATION	9.1 m Dia x 42 m (30 ft Dia x 128 ft 4.5 x 10^4 kg (9.9 x 10^4 lb) PER LAUNCH	3.81 x 10^6 kg (8.4 x 10^6 lb)	LIMITED EVA/IVA USED TO INSTALL OBSERVATORY MODULES USING THE MRMS AND OMV's
CREW CHANGEOVER	0	1	ASSEMBLY TEAM	20 PERSONS 2.3 x 10^3 kg (5 x 10^3 lb)	3.81 x 10^6 kg (8.4 x 10^6 lb)	NONE
	1	0	SOLAR OBSERVATORY INSTALLATION FOUR 425 kW SOLAR DYNAMIC UNITS	15.2 m Dia x 61 m (50 ft Dia x 200 ft) 2.27 X 10^5 kg (5 X 10^5 lb)	4.04 x 10^6 kg (8.9 x 10^6 lb)	LIMITED EVA/IVA TO INSTALL SOLAR OBSERVATORY USING THE OMV LIMITED EVA USED TO ERECT AND ASSEMBLE THE FOUR SOLAR DYNAMIC UNITS USING THE MRMS's AND THE OMV's
CREW CHANGEOVER	0	1	ASSEMBLY TEAM	20 PERSONS 2.3 x 10^3 kg (5 x 10^3 lb)	4.04 x 10^6 kg (8.9 x 10^6 lb)	NONE

TABLE 5-1. ATSS IN-ORBIT ASSEMBLY SEQUENCE (Concluded)

ASSEMBLY SEQUENCE	HLLV LAUNCHES	SHUTTLE LAUNCHES	PAYLOAD DESCRIPTION	PAYLOAD SIZE AND WEIGHT	CUMULATIVE MASS PROPERTIES	EVA AND ASSEMBLY AID REQUIREMENTS
	1	0	MICROGRAVITY FACILITY	15.2 m Dia x 61 M (50 ft Dia x 200 ft) 2.27×10^5 kg (5×10^5 lb)	4.27×10^6 kg (9.4×10^6 lb)	LIMITED EVA WITH EXTENSIVE IVA TO INSTALL FACILITY AND TRANSFER LIFE SUPPORT EQUIPMENT AND FUEL CELLS TO SAFE HAVEN
CREW CHANGEOVER	0	3	ASSEMBLY CREW ACTIVITIES COMPLETE 60 PERSON OPERATIONS CREW TAKES OVER SPACE STATION RESPONSIBILITIES	20 PERSONS 2.3×10^3 kg (5×10^3 lb) PER LAUNCH	4.27×10^6 kg (9.4×10^6 lb)	NONE
TOTAL LAUNCHES	25	13	–	–	–	–



A ORBITAL-MANEUVERING VEHICLE TRANSPORTING A SECTION TO MATE POSITION.

TELEROBOTICS PERFORM:

B POSITIONING FOR ASSEMBLY AND JOINING

C ASSEMBLY AND INSTALLATION OF SOLAR-DYNAMIC POWER UNIT

D INSTALLATION OF RADIATOR PANEL ASSEMBLY.

E AT COMPLETION THE TELEROBOTIC UNITS MOVE INTO THE BERTHING AND ASSEMBLY BAY FOR ASSEMBLY AND SERVICE OF OTHER SPACECRAFT.

Figure 5-9 Concept for the ATSS In-Orbit Assembly Operations Showing the Interaction of OMV and Telerobotic Units of the earliest flights. The schedule of shuttle launches interspersed with HLLV launches, allows crew changeover intervals that maintain fitness for the assigned assembly tasks. A total of ten shuttle flights will be required to transport assembly crews for the ATSS. Three additional flights will be required to change from the assembly crew to the operations crew of 60 people. The overall ATSS assembly time span projected as 30 months.

5.4 Mass Comparisons of Metals Versus Advanced Structural Composites

The launch costs and lift capability of projected HLLVs encourage mass reduction wherever practical. The mass for the baseline design of the ATSS is based on the use of aluminum alloys for the construction of all pressure vessels such as the torus cylindrical segments, telescopic spokes, and observatories. On the other hand, aircraft structure has been fabricated from structural composites that show mass reductions relative to conventional aluminum construction. The mass reductions range from 15 to 47 percent depending on the design, matrix material, and reinforcement selected (Reference 16). Figure 5-10 indicates the ultimate tensile strength for present aircraft materials and compares the strength of structural composites with the most-used aircraft metals. Among the metals, aluminum has the broadest acceptance and the largest applications data base.

The metals all show near isotropic properties. In contrast, structural composites may be highly anisotropic due to a preferred orientation of reinforcement plies. The ability to achieve a preferred strength direction within a composite laminate by orienting the predominant strength direction of each ply can yield a composite structure with great strength in one direction while strengths may be less in other directions. A synthetic resin-matrix composite structure having a preferred reinforcement orientation can surpass the tensile strength of titanium for 60 percent of the total mass of the same shape formed from aluminum. Application of advanced structural composites to aerospace vehicles has

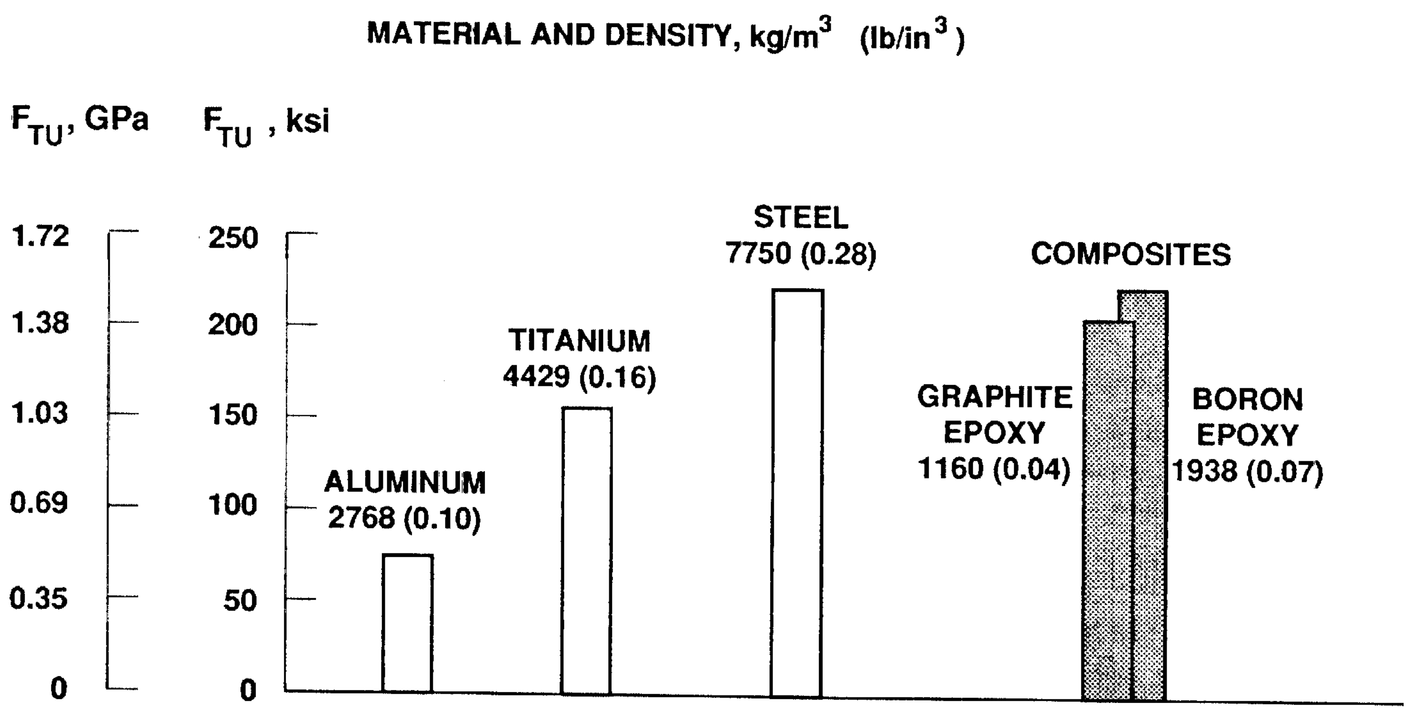


Figure 5-10, Comparison of Tensile Strength and Densities for Typical Aircraft Materials.

generated a substantial data base. As a further comparison, Table 5-2 (Reference 17) lists the mechanical properties of structural "I" beams made of steel, titanium, aluminum, and graphite epoxy composite. The moment of inertia (I) for each beam is identical to permit correlation of beam stiffness, "EI", and mass per unit length. The stiffness of the graphite/epoxy composite compares favorably with that of the steel beam at approximately one-fifth the mass. Judicious placement of composite reinforcement plies in the construction of structural members can equalize stress levels throughout the composite structure and thereby achieve a significant mass savings.

The presently available resin-matrix composites have a projected life of approximately eleven years in an orbital environment but the ATSS will need lifetimes of 15 to 30 years in orbit. Therefore, life extension sets the requirements for improvements in materials and processing methods.

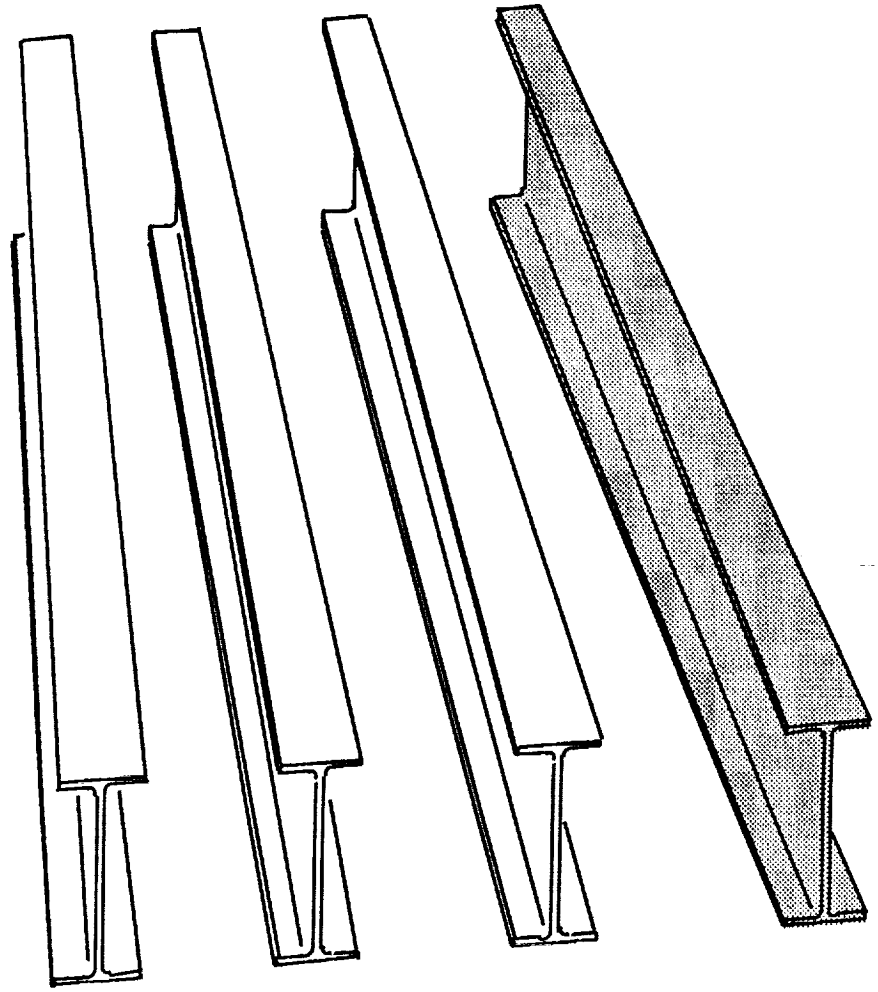
Large optical support structures and antenna systems in orbit must maintain their dimensional stability over a broad range of thermal excursions and therefore require materials having a near-zero coefficient of thermal expansion. For such applications, metal matrix composites (MMC) composed of graphite fibers with a high modulus of elasticity (E) embedded in an aluminum or magnesium matrix offer materials that combine a high specific stiffness, resistance to thermal deformation, a low coefficient of thermal expansion, and negligible outgassing. Therefore, MMC are candidate materials for the construction of dimensionally stable structures.

5.5 ATSS Materials Technology Selection Criteria

The ATSS will require improved structural materials that can be fabricated into structures and formed into enclosures which can endure the environments presented during prelaunch Earth storage, launch, and LEO. The selection of materials suitable for each ATSS application will require consideration of the following factors:

1. Definition of the requirements for each specific material application.

TABLE 5-2. COMPARISON OF PROPERTIES FOR A STRUCTURAL I-BEAM



	Steel A36	Titanium 6 Al-4V	Aluminum 7075-T6	Graphite/Epoxy Composite
Moment of Inertia, I **cm^4 (in^4)**	520.7 (12.51)	520.7 (12.51)	520.7 (12.51)	520.7 (12.51)
Modulus of Elasticity, E **GPa (10^6 psi)**	186 (27)	117 (17)	69 (10)	179 (26)
Stiffness, EI **MN-m^2 (10^8 lb-in^2)**	0.97 (3.38)	0.61 (2.13)	0.36 (1.25)	0.93 (3.25)
Ultimate Tensile Stress **MPa (ksi)**	552 (80)	1103 (160)	572 (83)	965 (140)
Mass per Unit Length **kg/m (lb/ft)**	7.7 (5.2)	4.3 (2.9)	2.8 (1.9)	1.5 (1.0)

2. Determination of the effects of critical environmental conditions on the properties of the material and possible interactions with other systems.
3. Qualification testing of the material for the intended application. Space flight presents a number of environments that result in unique damage mechanisms to exposed materials. These conditions are summarized in Table 5-3 (From Reference 6).

5.6 ATSS Assembly Methods and Mechanisms

Improved assembly methods and mechanisms are required for the in-orbit assembly of the ATSS. For example, the 24 cylindrical torus segments are assembled in a microgravity environment by joining the mating cylinder ends while maintaining a precise structural alignment and achieving a redundant, permanent, gas-tight seal between each of the segments. The use of retractable alignment guide pins, flange cam locks, and a mechanized flange attachment method are all needed to minimize the amount of EVA time associated with the torus assembly. The plan for assembling the torus must provide for the installation of the last segment and in addition must consider the potential for removal and replacement of a segment. In either case alignment and joining operations must be performed simultaneously at each end. In addition to the mating of cylinder ends, the ATSS utility plumbing and wiring between torus segments will require mating connections or disconnections; quick connect designs would expedite the assembly.

TABLE 5-3. DAMAGE MECHANISMS FROM THE SPACE ENVIRONMENT

ENVIRONMENT	DAMAGE
Ultraviolet Radiation	Creation of lattice defects in crystaline materials Chain scission in organic materials Free radical formation Color centers Crosslinking in organic materials
Charged Particle Radiation (Trapped radiation, solar winds, solar event particles, cosmic rays)	Creation of lattice defects in crystalline materials Recombination centers Absorption centers Chain scission in organic materials Secondary radiation damage
Presure (Atmospheric)	Volatilization of low vapor pressure fractions and materials Diffusion Vacuum welding
Thermal (Solar Electromagnetic)	Mechanical degradation, softening or embrittlement Chemical degradation
Micrometeoroid	Fracture or puncture
Electrodynamic Interations	Spacecraft charging
Atomic Oxygen Bombardment	Oxidized surface recession

6.0 ENVIRONMENTAL INTERACTIONS

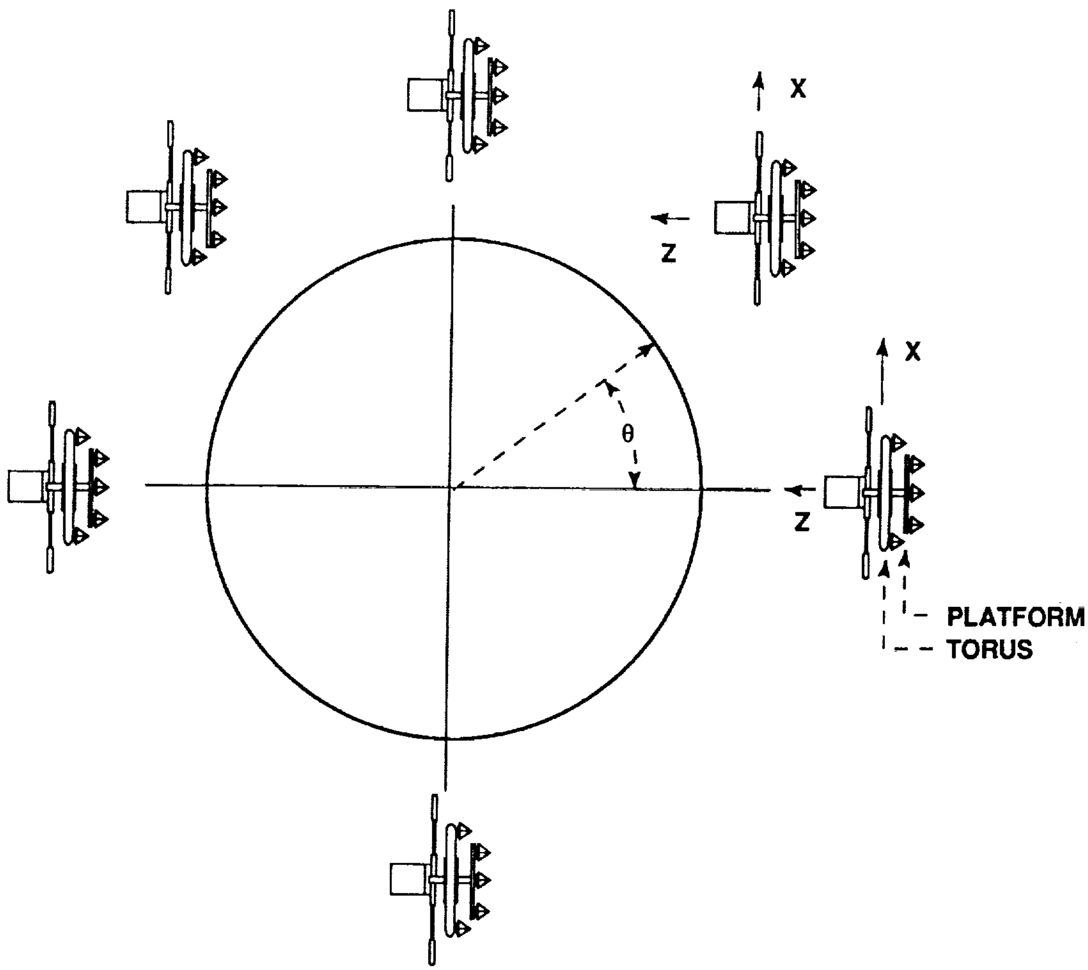
The external forces and torques acting on the ATSS are a function of the orbit position and the orbit itself. For the purpose of this study the ATSS is maintained in a Sun-facing attitude and is considered fixed inertially when calculating the disturbing forces and torques. The orbit parameters for the ATSS have been defined as circular at 500 km (310.6 miles) altitude with an orbit inclination of 28.3 deg. (Assuming launch from NASA Kennedy Space Center.) Figure 6-1 illustrates the orbital attitude and orientation of the ATSS.

The environmental forces and torques are those associated with aerodynamic drag (forces and torques), solar-radiation pressure (forces), and gravity gradient effects (torques). The following figures (From Reference 3) show these environments as a function of orbit angle; they were calculated by use of a module within the IDEAS[2] analytical program (Reference 5).

(1) Aerodynamic forces	Figure 6-2	(3) Solar radiation forces . . .	Figure 6-4
(2) Aerodynamic torques	Figure 6-3	(4) Gravity gradient torques . .	Figure 6-5

Because of the Sun-facing attitude and the symmetry of the ATSS, there are no torques associated with radiation pressure. In comparing the magnitudes of the forces and torques, the gravity gradient torque is more than three orders greater than either of the two aerodynamic effects.

The generation of electrical power from concentrated solar radiation necessitates a precise Sun-facing attitude and requires a precession at one revolution per solar year. This precession rate, although small, must be accomplished by active means.



Notes for a Solar Facing Orbit

1. θ is the orbit angle measured from solar zenith

2. y axis is positive away from the plane of view

Figure 6-1, ATSS Orbital Parameters.

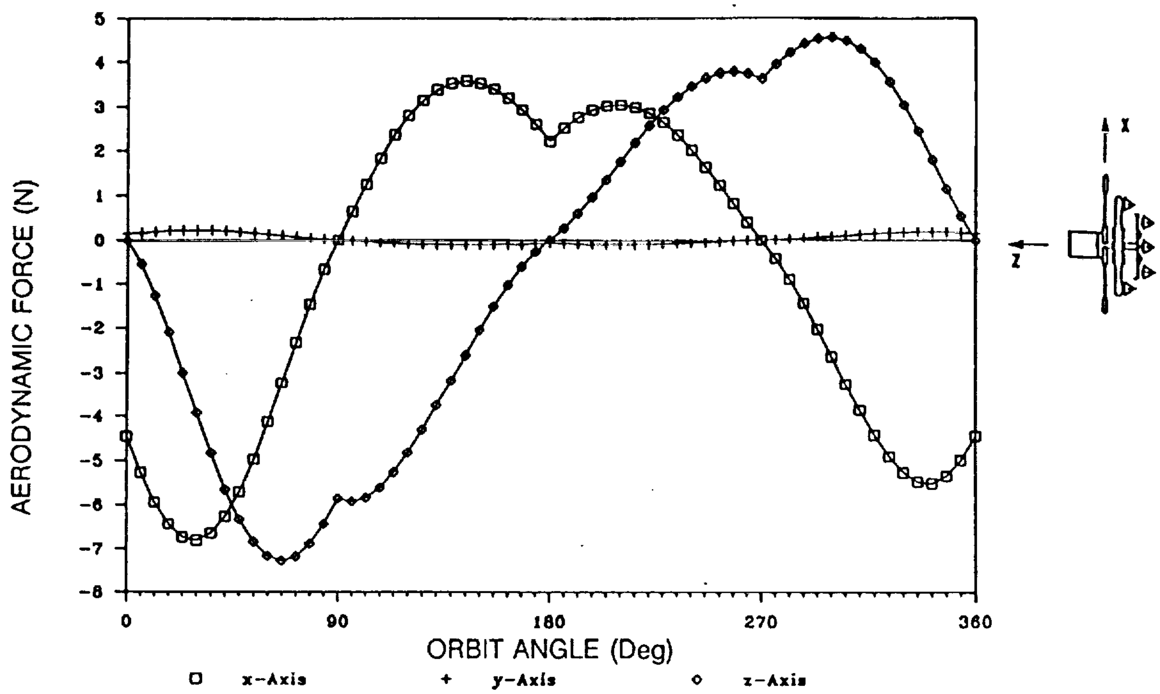


Figure 6-2, ATSS Aerodynamic Force as a Function of Orbit Angle.

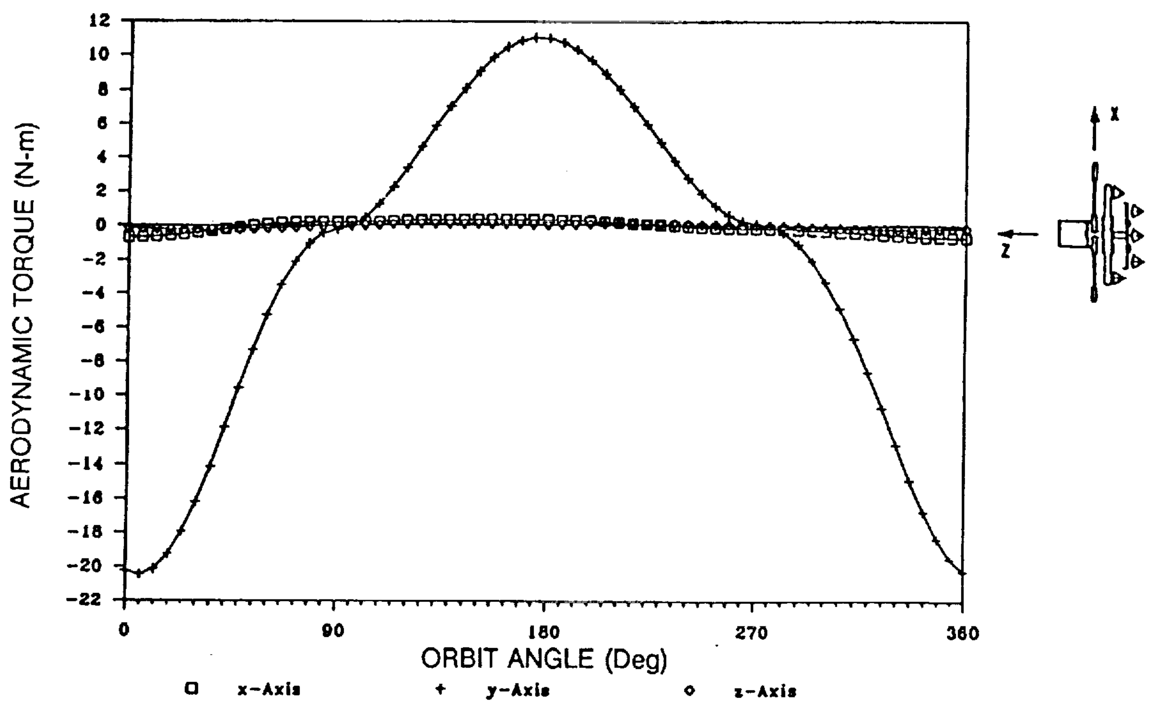


Figure 6-3, ATSS Aerodynamic Torque as a Function of Orbit Angle.

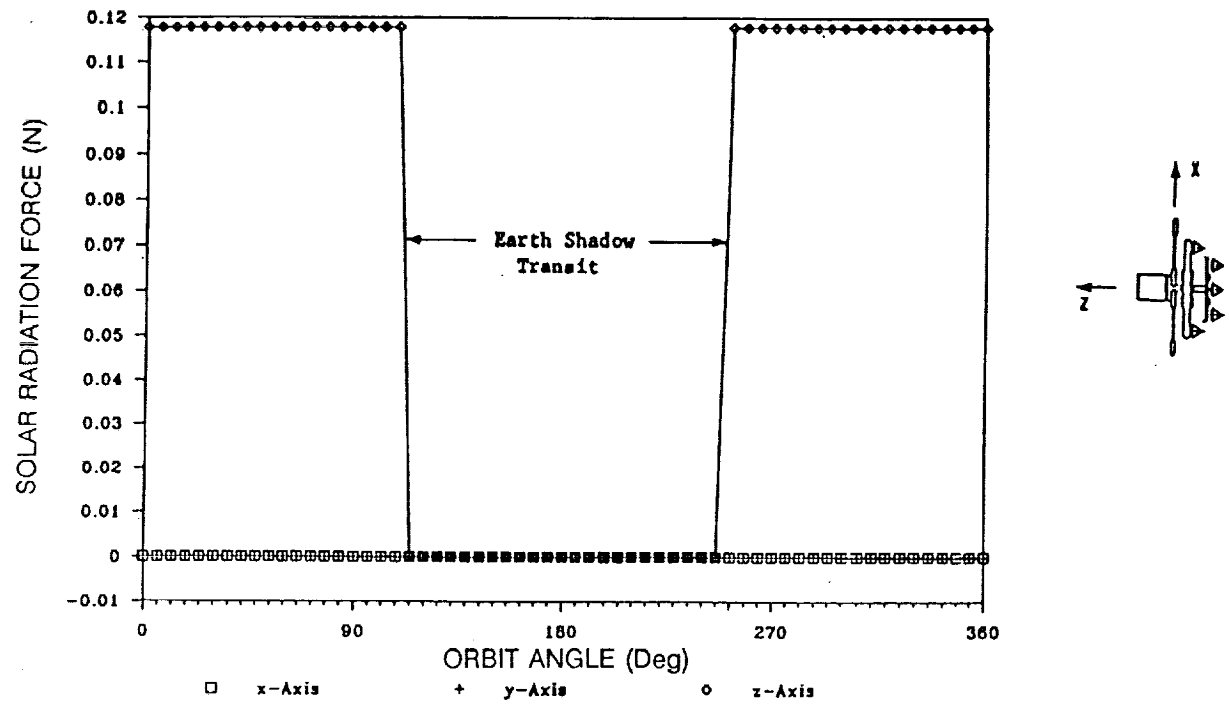


Figure 6-4, ATSS Solar Radiation Forces as a Function of Orbit Angle.

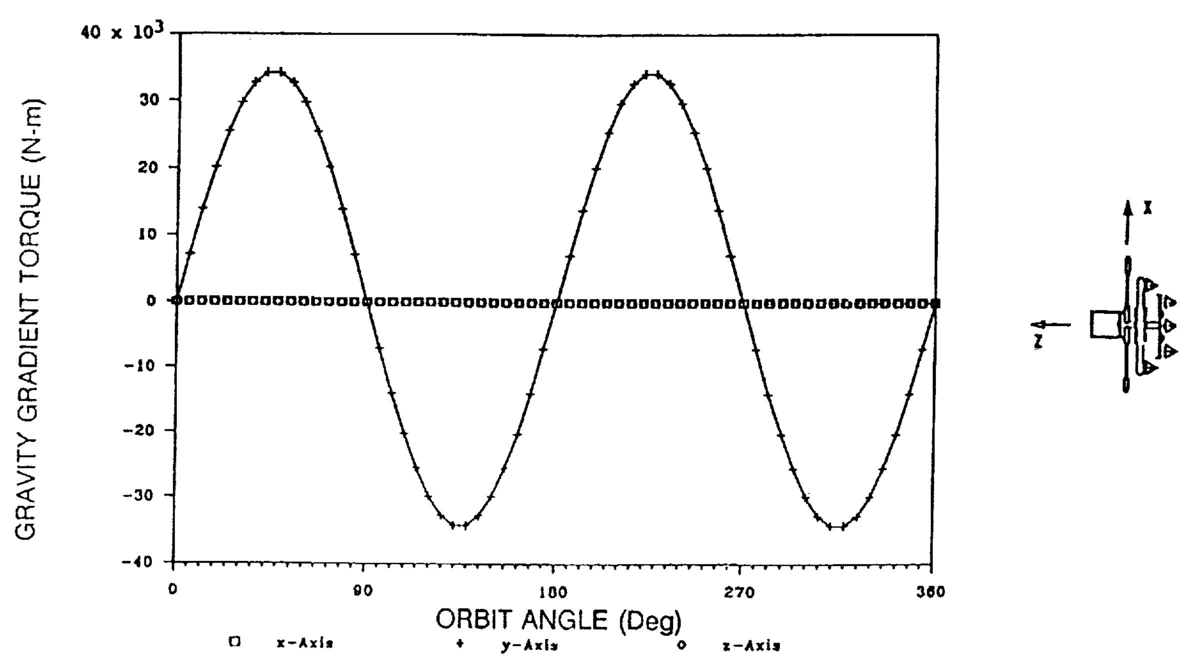


Figure 6-5, ATSS Gravity Gradient Torques as a Function of Orbit Angle.

7.0 VEHICLE ATTITUDE AND ALTITUDE CONTROL

The rotating ATSS must have an active attitude control to maintain the required orbital attitude and a reboost capability to maintain the orbit altitude. These requirements led to the examination of the following vehicle-dynamic and attitude-control functions:

1. Initial spin-up of the torus assembly to develop 1 Earth gravity.
2. Initial spin-up of the dual counterrotating tanks to balance the rotational momentum of the torus.
3. Precession of the ATSS to remain Sun-facing.
4. Orbital altitude maintenance to overcome aerodynamic drag.
5. Reaction to gravity-gradient torque disturbances.

The evaluation of the conceptual approaches for achieving these functions made assessments of a number of technology options for each of the requirements; and then selected a preferred approach for each function. The descriptions which follow first identify the preferred approach and then discuss some of the other options for implementation.

7.1 Initial Torus Spin-Up

The initial rotation of the torus section to a velocity sufficient to develop 1 Earth gravity will use a rotary-traction drive at the hub powered by electric motors. This drive system would maintain the rotation, counteract the drag friction of the seals, and accommodate small inertial disturbances within the torus assembly. The forces which generated the acceleration torque applied to the torus would be reacted by an equal and opposite drive system on the counterrotating ballast tanks. The torus requires an angular velocity of 0.293 rad/sec (2.8 rpm) to develop 9.8 m/sec^2 (32.2 ft/sec^2) centripetal acceleration at a 114.3 m (375 ft) radius. An alternative concept considered the use of H_2/O_2 chemical thrusters at the perimeter of the torus to develop the accelerating torque. However, for a torus with a moment of inertia of 3.2 x 10^{10} kg-m^2 (7.59 x 10^{11} lb-ft^2) and a propellant specific impulse of 4312 N-sec/kg, (440 sec), the estimated propellant mass required becomes 19,000 kg (41,890 lb).

7.2 Initial Spin-up of the Counterrotating Tanks

The precession requirement to maintain Sun-facing (Section 7.3, below) has led to the selection of dual tanks counterrotating relative to the torus which would null the rotational momentum and hence eliminate the gyroscopic reactions. A compatible set of design parameters was developed for a dual-tank arrangement, placing one tank above and one tank below the large torus with all three elements on the same axis of rotation. The tanks have a radius of 45.7 m (150 ft) and rotate at 1.047 rad/sec (10 rpm). Counterrotators to cancel the momentum of the torus required a mass ballast yielding a combined moment of inertia of 8.95×10^9 kg-m^2 (2.12×10^{11} lb-ft^2). Spin-up of the tanks utilized the equal and opposite torque from the torus as generated by traction motors at the hub. The use of H_2/O_2 for chemical propulsion with the thrusters on the rims of the counterrotator required an estimated propellant mass of 47,500 kg (104,700 lb).

7.3 Solar Precession

The selected approach to accommodating a one-revolution-per-year solar precession is the application of dual counterrotating tanks to cancel the rotational momentum of the torus. The elimination of the gyroscopic-reaction effects reduces the propellant requirement for precession to a negligible amount. The potential also exists for using the dual counterrotating tanks to generate the control moments necessary for counteracting the gravity gradient torques and these are discussed in Section 7.5 below.

A modified configuration, the ATSS without counterrotators, was considered. This configuration would have gyroscopic properties due to the spinning torus. The torque required to precess the ATSS was calculated from the gyro relationship and amounted to 1866 N-m (1376 lb-ft). If H_2/O_2 thrusters provided the torque from a location on the observatory tube approximately 125 m (410 ft) from the torus axis, the yearly propellant demand would total 109,200 kg (240,800 lb).

A precession torque generated by interaction with the magnetic field of the Earth was also evaluated. The concept consisted of a single loop of copper conductor around the periphery of the torus carrying an electrical current which interacted with the local field of the Earth to develop an 1866 N-m (1376 lb-ft) torque. The current requirement is 1330 amperes and, for an energy dissipation limit of 10 kW, the mass of copper wire was estimated at 15,000 kg (33,000 lb). If high-temperature superconductors become available, the magnetic torquing option may be a viable approach for solar precession and a possible means for controlling the rotation rate of the torus.

7.4 Orbital Altitude Maintenance

Aerodynamic drag on the ATSS will cause it to lose orbital altitude with time. The linear impulse required to balance the drag effect was computed for the ATSS configuration at 29,450 N-sec (6621 lb-sec) per orbit. This may be generated by a variety of propulsive options. For this study, chemical propulsion using H_2/O_2 and electrothermal propulsion options were evaluated. Chemical propulsion showed a propellant consumption for orbit maintenance of 6.83 kg (15 lb) per orbit, which totals 40,000 kg (88,200 lb) per year.

The maximum aerodynamic drag force is approximately 7 N (1.6 lb) as shown in Figure 2, therefore, a continuous thrust of approximately 5 N (1.1 lb) would appear to satisfy the ATSS requirement. This force could be provided by a cluster of several thrusters, and, since the direction is cyclic, would involve opposing sets operating at approximately a 50-percent duty cycle. The effective operating ranges for electrothermal thrusters are summarized in Figure 7-1, and show that both the resistojet and arcjet have practical ranges of thrust compatible with orbit maintenance for the ATSS.

Resistojets show thrust-to-power ratios that range from 0.13 to 0.31 N/kW (0.03 to

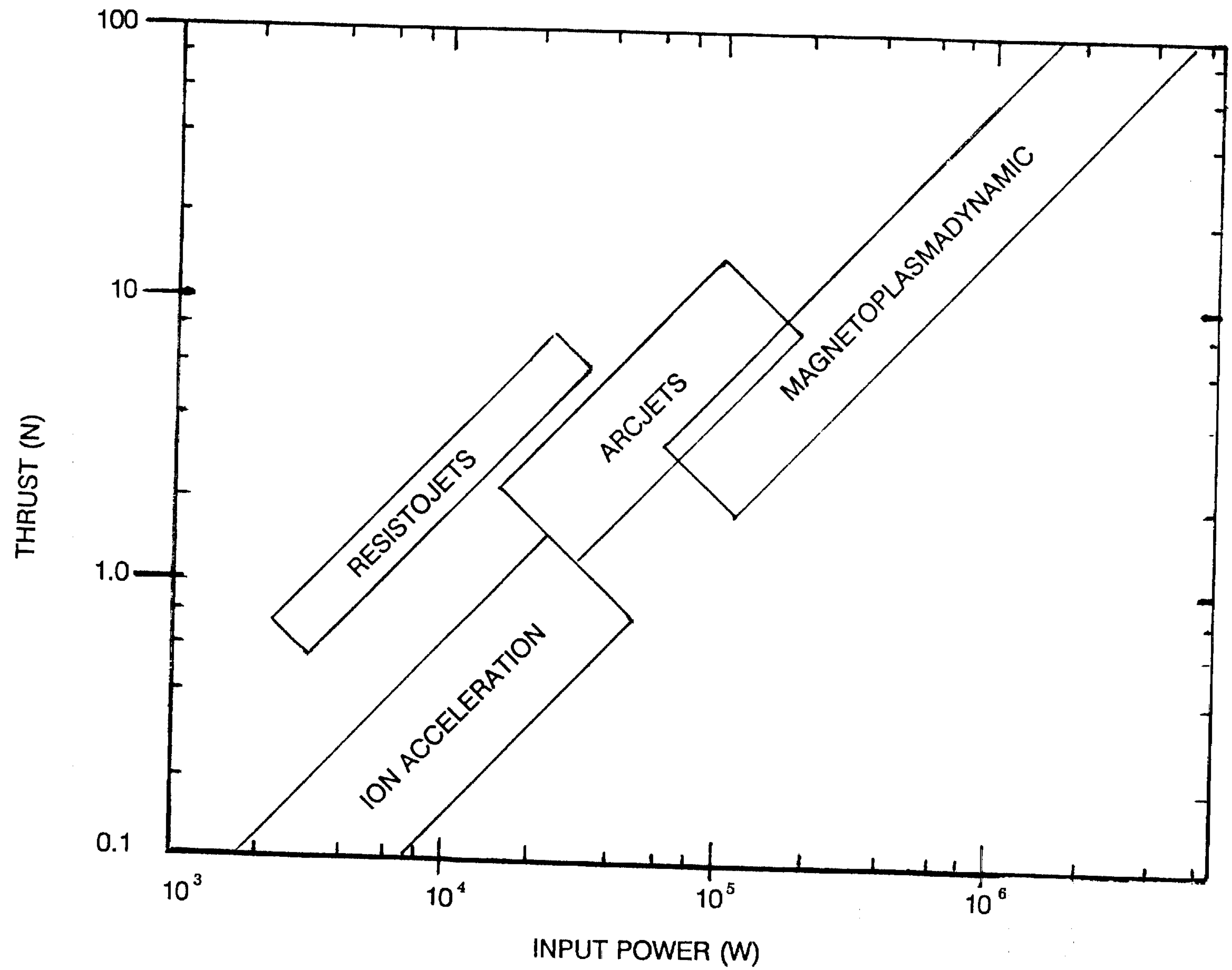


Figure 7-1, Operational Regimes for Electrical Thrusters.

0.07 lb/kW) (Reference 4); therefore, a 5 N (1.1 lb) thrust capability would require a continuous power usage that could range from 16 to 38 kW. An arcjet option, which has a thrust to power ratio range from 0.036 to 0.18 N/kW (0.008 to 0.04 lb/kW) would show a range of power demand from 28 to 140 kW for comparable service. In the ATSS, the hydrogen and oxygen used for propulsion and other needs is derived from the electrolysis of water. At an assumed 70 percent conversion efficiency, the electrolysis generates propellant gases at the equivalent of a 0.20 N/kW (0.045 lb/kW) thrust-to-power ratio for gaseous hydrogen and oxygen bipropellant thrusters operating with specific impulse of 4310 N-sec/kg (440 sec). For the ATSS application the 5 N (1.1 lb) continuous chemical thrusting would require 22.7 kW of power input. In comparing values for a continuous thrust of 5 N (1.1 lb), the power demand for a water resistojet and chemical propulsion would be effectively equal i.e, range from 16 to 38 kW or 22.7 kW, respectively. In comparing the propellant mass requirements, the projected specific impulse for a water resistojet is approximately 2942 N-sec/kg (300 sec); therefore, while a water resistojet would use approximately the same power as a H_2/O_2 combustion option, it would consume almost 50 percent more water as a propellant in the same application. A water resistojet would need an additional propellant mass of 2.7 kg (6 lb) per orbit, and would consume 54,700 kg (120,600 lb) per year. A resistojet or arcjet using hydrogen for the propellant operates with a specific thrust of about 9000 N-sec/kg (920 sec). The use of hydrogen for ATSS orbit maintenance would require only 24,000 kg (59,920 lb) per year. The mass reduction from the use of hydrogen is offset by an increased power demand to produce the hydrogen since only 11 percent of the water electrolyzed appears as hydrogen. The net effect on the ATSS system results in a continuous demand totalling 135 kW to produce 5N (1.1 lb) continuous thrust from a resistojet. This power demand is about six times that required for a water resistojet and represents about 5 percent of the total generating capacity of the ATSS. The power requirements for arcjets are proportionally greater. The use of hydrogen as a propellant for these electrothermal options could become practical if hydrogen or ammonia were supplied from the Earth as part of the logistics support.

7.5 Gravity Gradient Disturbance Reaction

The gravity gradient torque associated with the Sun-facing attitude of the ATSS is illustrated in Figure 6-5. The predictions show a maximum unbalance of 34,000 N-m (25,000 lb-ft) that must be reacted or nulled by some means. This gravity gradient torque is generated by the difference between the moment of inertia about the Sun-facing axis and the moment of inertia about a perpendicular axis in the plane of the orbit. Gravity gradient torques exist in any spacecraft that must operate inertially fixed (e.g. Sun or Stellar pointing). The torque effects increase with spacecraft size, and become critical considerations for rotating spacecraft that must operate stably in a Sun-facing attitude. In summary, for any spacecraft that flies inertially fixed, if the ellipsoid of inertia is not a sphere, it will have to contend with gravity gradient forces. In that context, the ATSS illustrates the potential magnitude of such forces and the impact on means for control. The ATSS study evaluated the three options of propulsive reaction, present gyroscopic equipment and an advanced technique using the features of the ATSS itself.

7.5.1 Propulsion Reaction

An active propulsion system that reacts 34,000 N-m (25,000 lb-ft) of torque cycling two times in an orbit period consumes an unacceptable quantity of propellant.

An initial evaluation considered eight hydrogen-oxygen thrusters operating simultaneously in reaction to the gravity gradient torque. At a specific impulse of 4310 N-sec/kg (440 sec), the propellant requirement for an orbit totalled 717 kg (1,581 lb). This corresponds to 3.9×10^6 kg (8.6×10^6 lb) per year for gravity gradient reaction and is impractical. Propellant use appears as a limiter for active propulsion techniques applied to gravity gradient torques.

7.5.2 Conventional Gyroscopic Techniques

The evaluations of conventional items considered existing control-moment gyros (CMGs) and dual counterrotating annular momentum control devices. Both elements absorb torque by deflecting the plane of rotation for a gyroscopic element. An optimum application makes the maximum displacement of the gyro wheel absorb the total angular momentum. For the ATSS, the angular momentum capacity of the gyro has to be about 15.5 x 10^6 N-m-sec (11.43 x 10^6 lb-ft-sec) in each direction to accommodate 31 x 10^6 N-m-sec (22.9 x 10^6 lb-ft-sec) by a limit-to-limit deflection of the rotor.

The maximum gravitational torque and associated angular momentum, 34,000 N-m (25,000 lb-ft) and 15.5 x 10^6 N-m-sec (11.43 x 10^6 lb-ft-sec) respectively, set the requirements for a momentum control system. These values are several orders of magnitude greater than available with current CMGs. For example, one of the higher capacity CMGs (Reference 4) is a double-gimbal unit having an output torque of 272 N-m (200 lb-ft) and angular momentum capacity of 6100 N-m-sec (4500 lb-ft-sec). This unit weights approximately 295 kg (650 lb). The ATSS would require approximately 126 of these gyros just to produce the necessary torque and these would add about 37,000 kg (82,000 lb). The angular momentum requirements are even greater, and would require about 2546 gyros, with an additional mass of about 748,000 kg (1.65 x 10^6 lb).

A dual counterrotating wheel control-moment gyro configuration was evaluated. In this approach, the spin axes of the two wheels are angularly displaced to generate the torque reaction. The angular momentum of the wheels and the maximum angular displacement for the rotating axes establish the moment control capability. The maximum wheel momentum is limited by the material and wheel geometry. Several options of metal and composite wheels of various geometrics were evaluated (Reference 4). The results showed that a glass fiber reinforced, thin-rim flywheel with a radius of 50 m

(164 ft) and a 5 degree allowable deflection angle requires a two-wheel subsystem mass of approximately 14,000 kg (30,870 lb) to achieve the gravity gradient-torque compensation. The dual wheel approach shows promise for the large scale storage of kinetic energy in a system which combines energy storage with attitude control.

7.5.3 ATSS Features, Use of the Counterrotators for Control

In actuality, the ATSS must simultaneously null two torque effects. The one-per-year precision has to continue without disturbance from the gravity gradient. The control-moment gyros and the dual counterrotating wheels have rotational inertias which can contribute to the one-per-year requirement, however, the contribution is only a few percent of the requirement even for the dual wheel configuration. The use of the counterrotators for cyclic reaction control appeared as an inverse approach; use the large momentum necessary for Sun-pointing as the nulling element for gravity gradient torques. In such an application, the counterrotators are tilted in unison to counteract the torque. For the ATSS counterrotators the required tilt is about 0.2 deg. These angles are small enough to cause no appreciable change in the angular momentum about the axis of symmetry. The means for implementing the tilt control would have to be incorporated into the drive systems for the torus and counterrotators. These were considered as one more input to the drive system compliance requirements that were already addressing both the planes of rotation and the centers of rotation in an active dynamic environment. This small cyclic tilt approach appears feasible and has been selected as the baseline option for the ATSS.

8.0 ELECTRICAL POWER GENERATION SYSTEM COMPARISONS

The ATSS studies included a comparison of electrical power generation system options (References 3 and 4), using the initially defined configuration of 2.5 MW continuous electrical output supplied by six identical solar dynamic units as the baseline. Selection of a 425 kW output solar dynamic unit as the modular generating element could possibly apply to growth versions of Space Station Freedom; however for this study it provided a means for assessing technology requirements over the broadest range of disciplines. In such systems, solar concentrators become large area space structures with close tolerances for the surface accuracy. Solar collectors must accomplish high temperature heat transfer and energy storage; and converters also have high temperature heat transfer requirements determined by an overall conversion efficiency. The ATSS study set the overall efficiency at 40 percent for converting heat input to electrical output and defined converters as closed cycle gas turbines driving 400 Hz, 440 V alternators. The dynamic system elements include: heat exchangers, regenerators, radiators, compressors, turbines, and rotating alternators. A continuing study compared alternate heat sources as inputs to the same dynamic converters. Heat sources selected for comparison were concepts for nuclear fission, radioisotope decay, and deuterium-tritium fusion. In addition, advanced photovoltaics with advanced energy storage elements provided a passive energy conversion alternate.

The configurations for each of the alternate systems were also chosen to address the definition of technology requirements. Wherever performance or capability improvements could be identified, improved values became part of the definition and were applied to such elements as the conversion efficiency of gas turbines and energy storage capability for flywheels. For other portions of the systems, configurations utilized existing conventional materials or practices as a means to show margins for improvement in elements such as structure, heat rejection radiators, and high temperature thermal insulators.

Configurations for each of the five systems were compared in terms of total mass, control requirements and configuration-particular concerns. Each of the systems show essentially continuous operation and each has some unique features or operating requirements at points in time during the baseline ten-year functioning life. The principal features of the five systems are summarized in Table 8-1, and Figures 8-1 through 8-5 show the heat based systems, Figure 8-6 shows a solar photovoltaic panel concept.

The concept for the solar dynamic system, shown in Figure 8-1, includes a pedestal-type mounting at the center of the concentrator to allow for precise Sun-pointing. In operation, the focal point of the concentrator must be kept within the aperture of the collector. Figure 8-2 shows the cross section through the collector-converter assembly. The collector cavity is cooled by a liquid metal loop which absorbs the solar input energy and melts phase change material. The converter uses a counterflow of sodium-potassium (NaK) liquid metal to extract heat by solidifying phase change material, and transfers that energy to the gaseous nitrogen stream feeding the converter turbine. Turbine exhaust flows through a counterflow regenerator and a water cooled precooler before entering the compressor, and precooler water flow circulates through an external radiator. The baseline configuration has defined cycle efficiencies and operating temperature ranges to result in approximately equal areas for solar concentrators and heat rejection radiators. The NaK liquid metal loop with two heat exchangers, the regenerator, the turbine-alternators, and the radiators are common items for all heat-source based systems.

The fission reactor shown in Figure 8-3 is an extension of homogeneous core concepts using metal-clad core components. Among candidate liquid metals, sodium appears as the first choice for a space-based system when considering interactions with neutrons, chemical activity, and total mass. Dual cores in a common shield provide a degree of redundancy to the system.

The radioisotope concept shown in Figure 8-4 is based upon Pu^{238} which has been the isotope of choice for space power applications. This isotope is not presently available

TABLE 8-1. SUMMARY OF FEATURES FOR ATSS ELECTRICAL POWER GENERATING SYSTEMS

SYSTEM	SYSTEM FEATURES AND DESCRIPTION	CONTROL REQUIREMENTS	PARTICULAR CONSIDERATIONS
Solar Dynamic	Six identical units, four on the platform two on the torus. Full paraboloid of revolution concentrator with collector-converter assembly at focus. Each unit stores energy in phase change material during illumination, recovers energy during dark transit. Delivered electrical output is 425 kW per unit as 400 V three phase AC driven by closed cycle gas turbines operating at 0.4 thermal to electrical conversion efficiency. (Same converters used for all heat source systems)	• Precision pointing • Sunset-sunrise transitions • Energy storage • Thermal environment for the collector-converter assembly	• Optical alignment during on-orbit assembly • Start up-shutdown transient • Precision pointing on a rotating torus
Fission Reactor	Two cores of enriched U^{235} moderated by BeO with liquid sodium coolant. Each core drives three converters through liquid Na to NaK heat exchangers. Both cores and all six heat exchangers are within a common radiation shield. Options: Radiation shields as lead, steel, concrete, and water	• Reactor heat extraction o Converter heat transfer o Radiation environment monitor o Provisions for emergency shutdown	• Recovery of radioactive materials at end of life
Pu^{238} Radio-isotope Decay	Two cores of PuO_2-BeO mix each driving three converters. Core NaK coolant has direct heat exchange into the gas turbines. Both cores within a common radiation shield. Options: Radiation shields as lead or steel.	• Core heat transfer • Core start-up and shutdown transients	• Thermal control of fuel elements during launch, delivery to orbit, on-board preparation and return from orbit at end of life

TABLE 8-1. SUMMARY OF FEATURES FOR ATSS ELECTRICAL POWER GENERATING SYSTEM (concl.)

SYSTEM	SYSTEM FEATURES AND DESCRIPTION	CONTROL REQUIREMENTS	PARTICULAR CONSIDERATIONS
Fusion: Inertially confined, laser ignited	Single reactor cavity with flowing liquid lithium walls. Fuel pellet injection and ignition by dual feeds and dual lasers. Reactor lithium flow is scavenged to recover tritium formed during fusion. Eight converters powered by liquid Li to NaK heat exchangers.	o Reactor liquid metal flow balance o Fuel encapsulation feed o Laser timing and pulse generation o Reactor internal environment control o Extraction and separation of gases and products of fusion o Liquid metal heat transfer	• Installation and start-up power andrequirements
Advanced Photovoltaic	Advanced photovoltaic cell arrays deliver 0.2 solar input as electrical power at 280 V DC. Solar panels on both torus and platform. Energy stored during illumination is recovered during dark transit. Optional methods for energy storage: advanced batteries O_2/H_2 fuel cells, and advanced flywheels.	o Energy storage input o Energy recovery operation o Sunset-sunrise transitions	• Thermal control during installation and start-up • Space debris impact damage • Low natural frequencies (if not mounted on board-like structures)

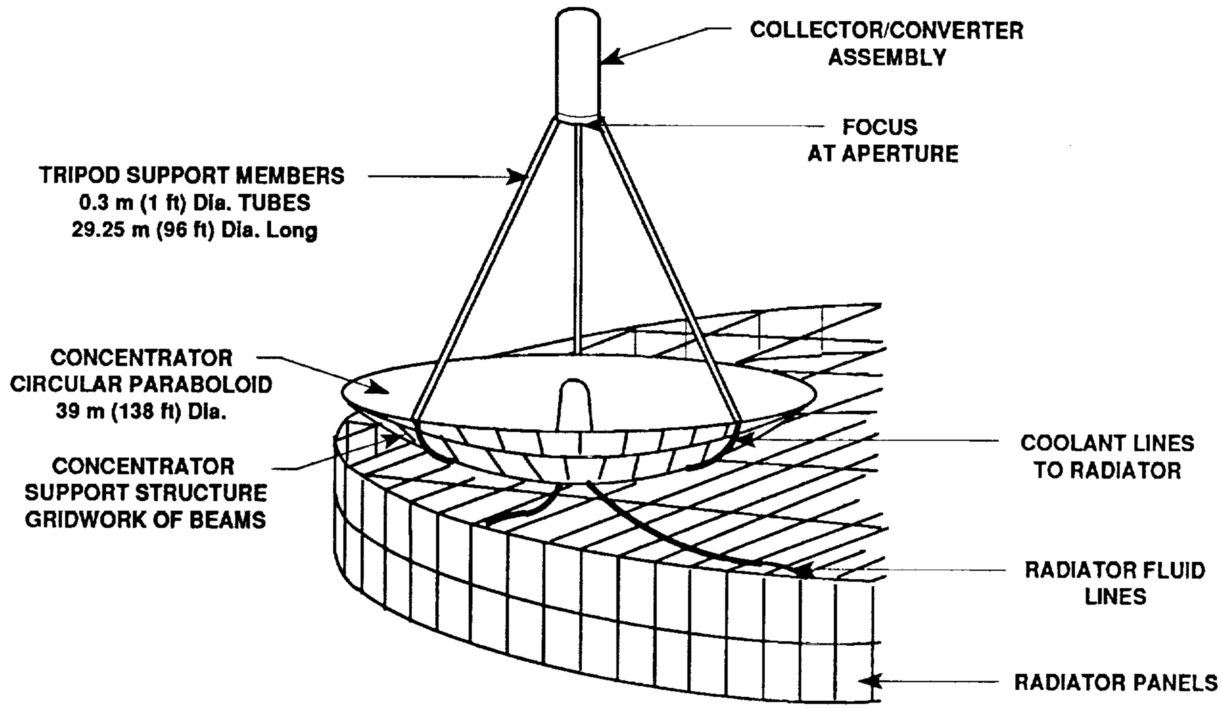


Figure 8-1, Concept for the ATSS Solar Dynamic Power Unit.

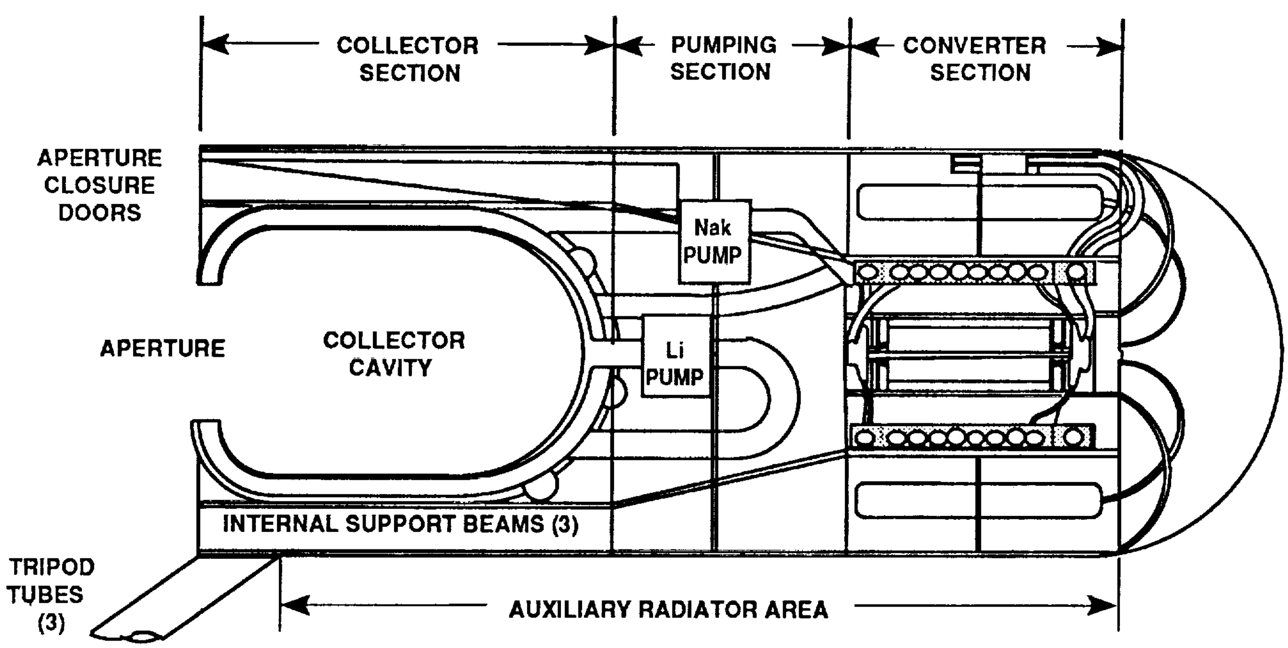


Figure 8-2, Cross Section Through the Collector and Converter of an ATSS Solar Dynamic Power Unit.

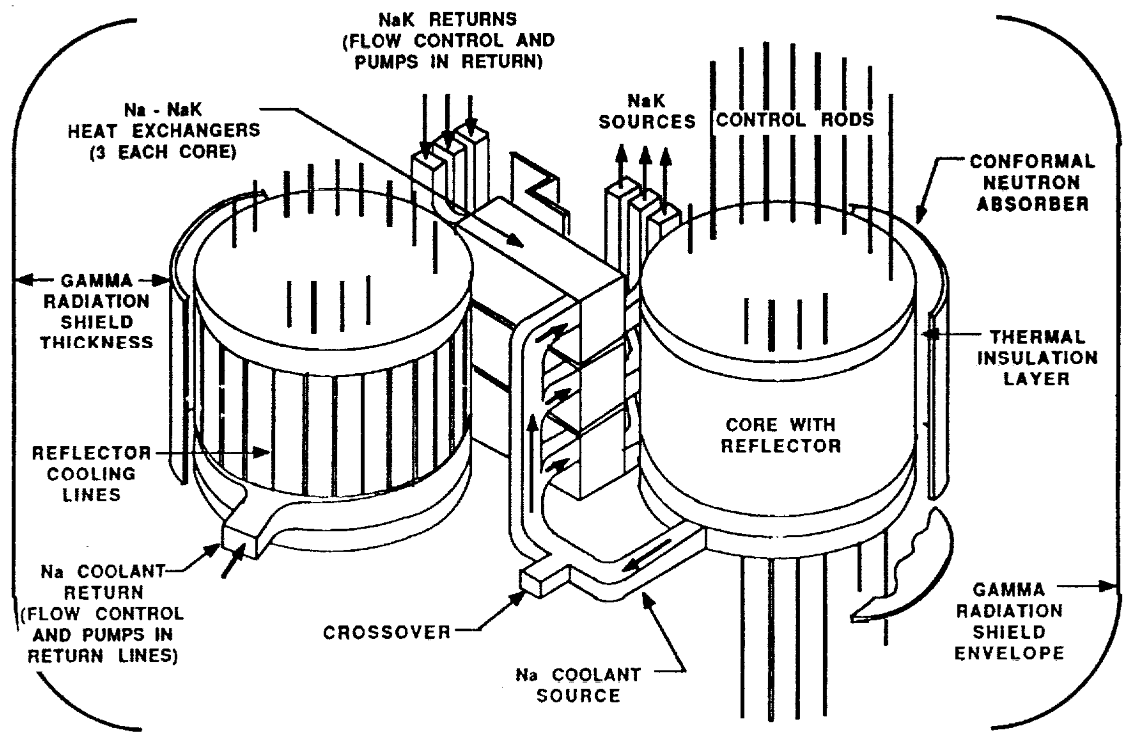


Figure 8-3, Concept for an ATSS Dual Core U^{235} Fission Reactor Heat Source.

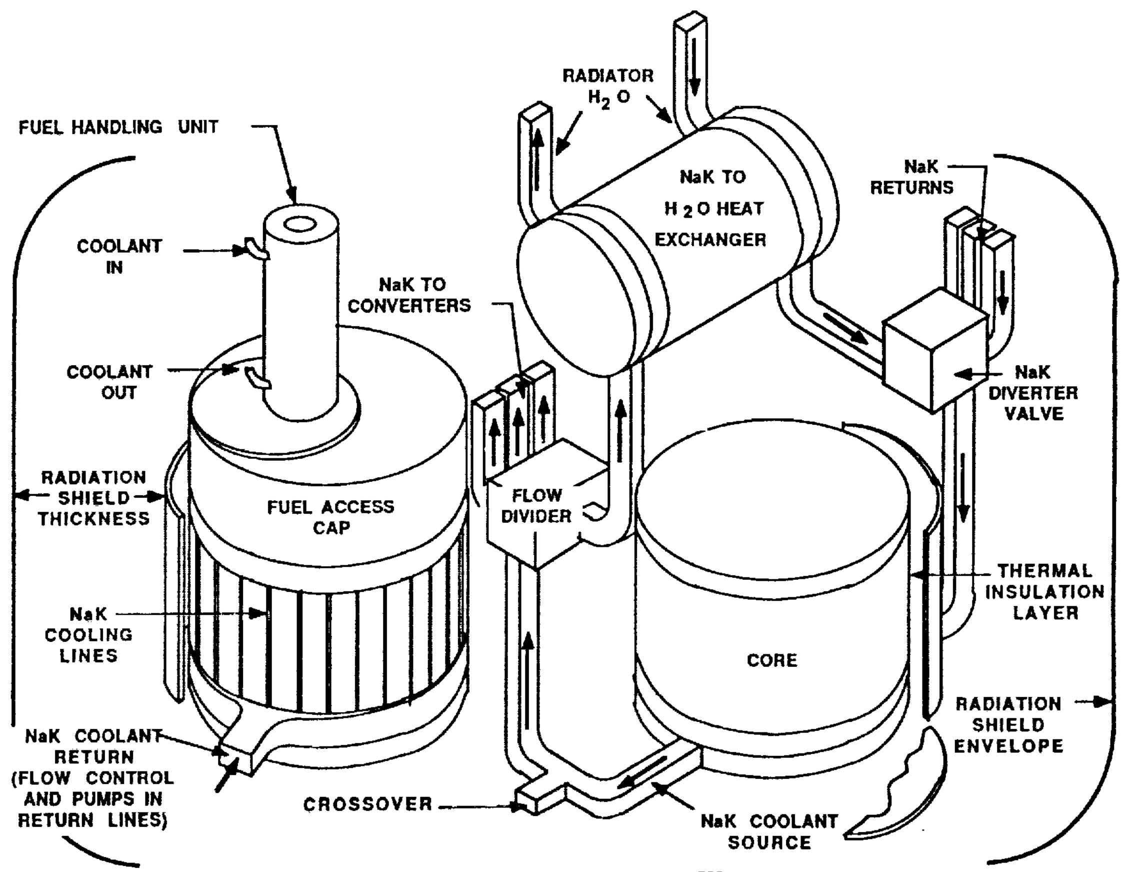


Figure 8-4, Concept for an ATSS Dual Core Pu^{238} Radioisotope Heat Source.

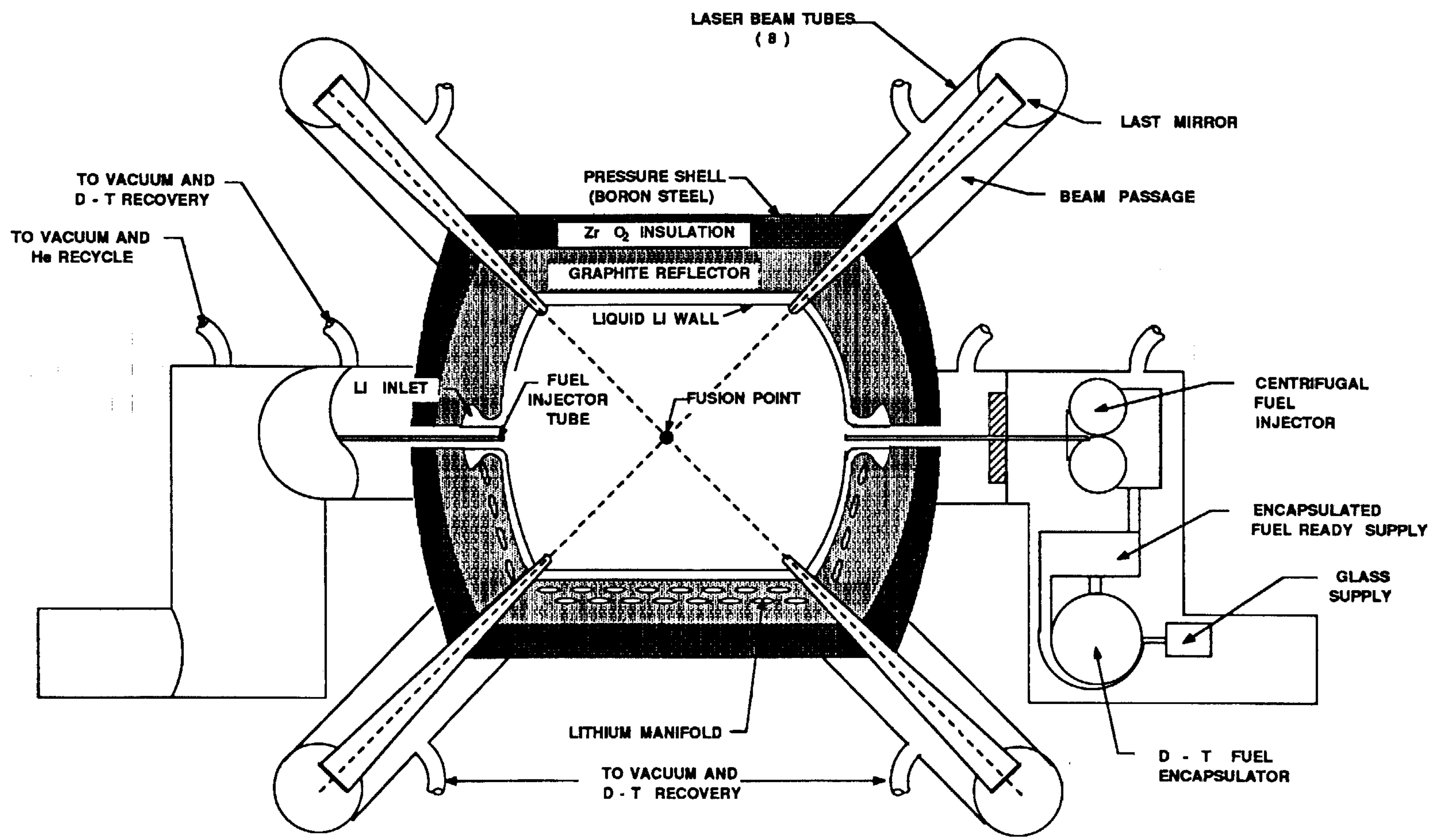


Figure 8-5, Concept for an ATSS Fusion Reactor, Using Inertial Confinement and Laser Ignition.

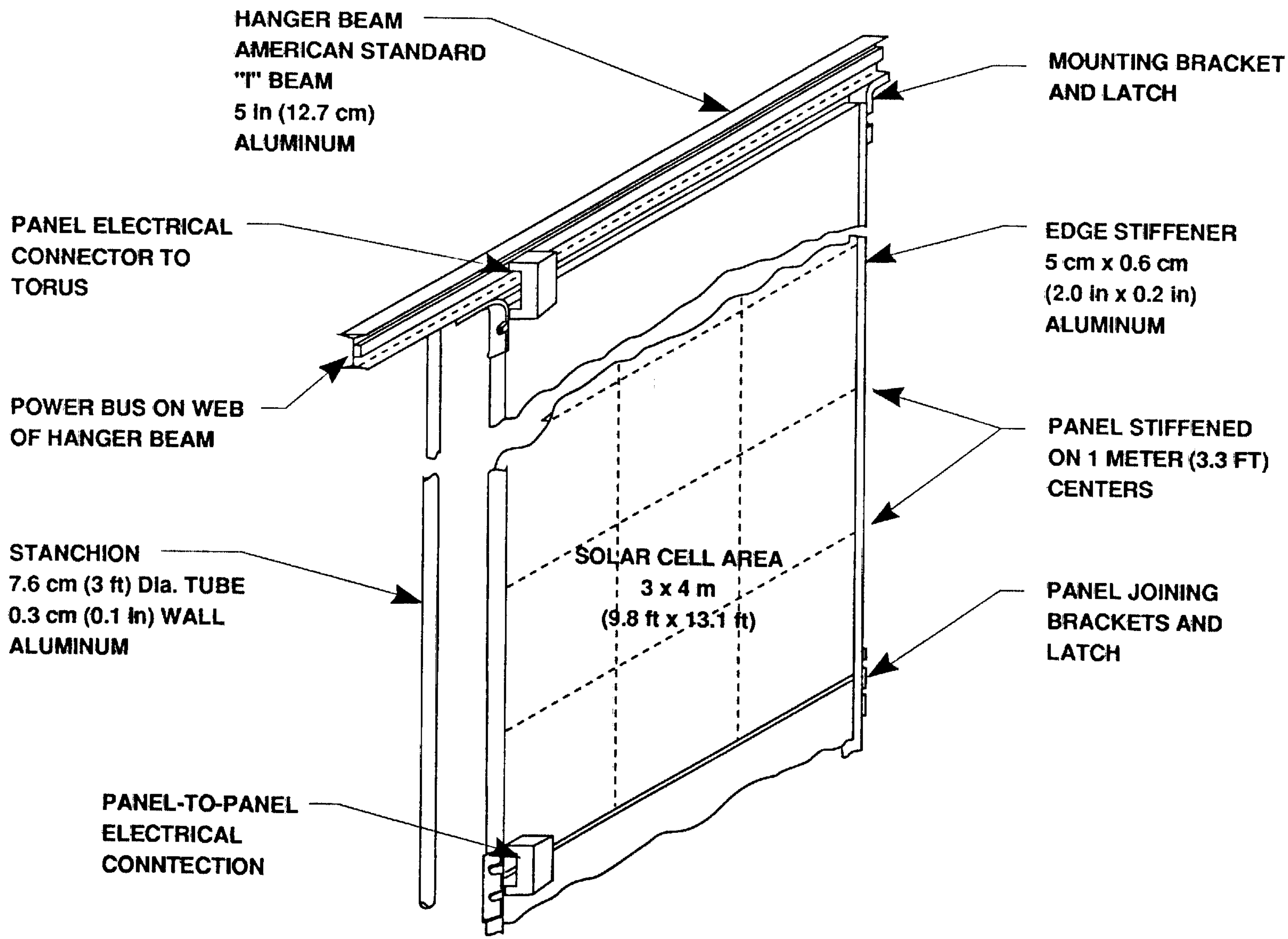


Figure 8-6, Concept for an ATSS Photovoltaic Panel Installed on the Rotating Torus.

in the quantities required (Reference 4); however, a national policy decision to reprocess nuclear power plant fuel would generate quantities of Pu^{238} as a by-product. The radioisotope configuration retains the dual core concept of the fission reactor but only needs the NaK liquid metal loop for energy extraction.

The configuration for the fusion system utilized present developments in high-energy ultra-violet wavelength lasers as the basis for selecting a laser-ignited, inertially confined fusion reactor. Figure 8-5 shows the cross section through the reactor system. In operation, the fuel system encapsulates a deuterium-tritium mixture and injects pellets into the center of the reactor chamber. Energy from the laser pulse (as eight overlapping beam spots) implodes each pellet to provide confinement and heats the mixture to initiate fusion. A flowing liquid lithium wall (the configuration requires microgravity) absorbs the products of fusion as photons, neutrons, and residual gasses. Neutrons interact with lithium to produce tritium necessary for fuel. The configuration shown has redundancy in fuel feeding systems and in laser igniters. Fuel consumption to yield 2.5 MW continuous electrical power delivery amounts to 0.78 kg (1.72 lb) per year for a system of this type.

The advanced photovoltaic system requires a sustained solar cell conversion efficiency in the range of 22 to 25 percent to provide an overall system conversion efficiency of 20 percent. Present solar cell research has identified some candidate configurations. For ATSS application, cells were assumed to operate stably in thermal equilibrium without need for external cooling if the back sides of solar panels radiated to dark space. The ATSS has solar-facing areas on the platform and around the inner radius of the torus sufficient to provide 2.5 MW continuous if throughput efficiency is in the range of 18 to 20 percent. Battery systems evaluated for energy storage included Ni-Cd as existing technology, Ni-H_2 cells from Space Station Freedom, and Li-Na-Sulfur as advanced technology. All batteries operated with an 80 percent depth of discharge. In addition, electrolytic decomposition of water as an electrical load leveler made O_2/H_2

fuel cells a most advantageous choice for chemical storage of energy. Flywheel configurations considered the best available steel, glass composites operating with the present limit at 40 percent of the fiber tensile ultimate strength, and advanced graphite fiber composite operating with a steel-equivalent limit at 65 percent of fiber tensile ultimate strength. All flywheels operated with a 50 percent change in rotation (75 percent of energy stored).

All five of the power systems need to operate under single-point continuous output conditions. Alternating current generators establish their frequency by rotation speed and their output voltage by a rotating magnetic field; both must remain constant. Solar dynamic systems have to extract all the energy stored in phase change before accepting the next solar input; a similar storage condition exists for solar photovoltaics. Radioisotope decay releases energy continuously with only a slow decrease as defined by the half life of the isotope. Fusion systems operate as a complex interactive balancing among a number of subsystem functions. The output of a fission reactor can be varied; however, once the system has been stabilized at a power level, products of fission begin to limit the operating range, and after a shutdown, core cooling is required. Therefore all of these systems need to operate into a constant electrical load, and for the ATSS, electrolysis of water provides that capacity.

8.1 Comparison of System Masses

The comparisons of systems masses coupled with estimates of the masses for the elements of the system provide an insight into three pertinent areas. First they show the overall needs for technology advances. Second they identify the particular areas requiring improvements and finally they also identify those features which have a limited capability for change. Masses generated from the configurations used for the study are intended for relative comparisons, therefore Table 8-2 lists the masses in kilograms only and also shows the relative contribution from each principal section of the system and identifies

TABLE 8-2. COMPARISON OF MASS CONTRIBUTIONS FOR THE ATSS POWER SYSTEM ALTERNATIVES

MASS CONTRIBUTIONS	POWER SYSTEM ALTERNATES				
	SOLAR PHOTOVOLTAIC	RADIOISOTOPE DECAY	FUSION	SOLAR DYNAMIC	NUCLEAR FISSION
Mass Total, Kg	86251 to 105934	330537 to 342352	412900	414858	398105 to 1899970
Thermal Energy Elements, kg		33340 (10%) Pu^{238} Fuel Mix Cladding Heat Transfer Elements	73870 (18%) Reactor Fuel Feed Lasers and Optics Separators Heat Exchangers	56628 (14%) Collector Assy Phase Change Matl. Heat Transfer Elements	13622 (3%) Core Control Rods Heat Transfer Reflector
Electrical Conversion, kg	61677 to 73480 (70% to 74%) Photovoltaic Panels Batteries Flywheels or Fuel Cells	16662 (5%) Converters Heat Exchangers Controls	22216 (5%) Converters Heat Exchangers Controls	16662, kg (4%) Converters Heat Exchangers Controls	16662 (5%) Converters Heat Exchangers Controls
High Temperature Thermal Insulation (ZrO_2) kg		15698 (5%) Core Blankets Converter Heat Exchangers	69598 (17%) Reactor Blanket Heat Exchanger Blanket Converter Heat Exchangers	32982 (8%) Collector Blanket Converter Heat Exchangers	11126 (2%) Core Blankets Converter Heat Exchangers
Structure, kg	16175 to 18025 (16% to 17%) Panel Mounts	Included in Heat Transfer and Shielding	Included in Reactor	135804 (33%) Concentrators Tripods Collector Converter Housing Mounting Pedestals Aperture Doors	Included in Core, Heat Transfer and Shielding
Radiators, kg	4008 to 14429 (4% to 13%) Energy Storage Heat Sink	163536 (49%) Precoolers	245304 (60%) Precoolers Laser	167628 (41%) Precoolers Secondary Radiator	163536 (42%) Precoolers
Radiation Shields, kg	None	101305 (31%) Lead 113120 (33%) Steel	Included in Reactor and Reactor Blanket	None	193163 (48%) Lead 233693 (53%) Steel 562333 (73%) Concrete 1695028 (89%) Water

the particular contributing elements. The systems are listed in ascending order of mass and are based upon existing technology for high temperature insulation, structures, radiators and radiation shielding. Figure 8-7 shows a comparison of system masses in terms of mass-to-power ratio presented in the order they were addressed during the study. For cases of the solar dynamic and nuclear fission systems, mass to power ratios include both an initial estimate (from Table 8-2) and an estimate showing effects of improved technology. Estimates for radioisotope decay, fusion and photovoltaics consider only an advanced technology configuration. These comparisons lead to the following assessments presented in the order shown by Table 8-2.

A. Photovoltaics

An advanced technology photovoltaic-based power system will remain a candidate for any Earth-orbiting space vehicle. Advantages in mass relate directly to achievements in the conversion efficiency of solar cells. Energy storage will keep the options of batteries, fuel cells and flywheels with the particular storage technique determined by the application. For an ATSS type of operation, synergy with water usage makes O_2/H_2 fuel cells an attractive choice. A photovoltaic system that requires auxiliary cooling by radiators loses some mass advantage. In such a context, the concept of concentrating solar input by reflecting surfaces offers no mass advantage. Masses associated with supporting structure for the concentrators and radiators required for cooling solar cells can triple the mass of an equivalent open system.

B. Radioisotope Decay

A radioisotope decay heat source offers the advantage of continuous power and some relief from stringent Sun-pointing requirements. An initial estimate for the system mass showed radiators and shielding as the major contributors. These elements continue as the major contributors to an advanced technology configuration. For radiators, heat rejection rates and operating temperatures are fixed by the thermodynamic cycle of the converters, however, advanced materials and techniques make a 50 percent reduction in

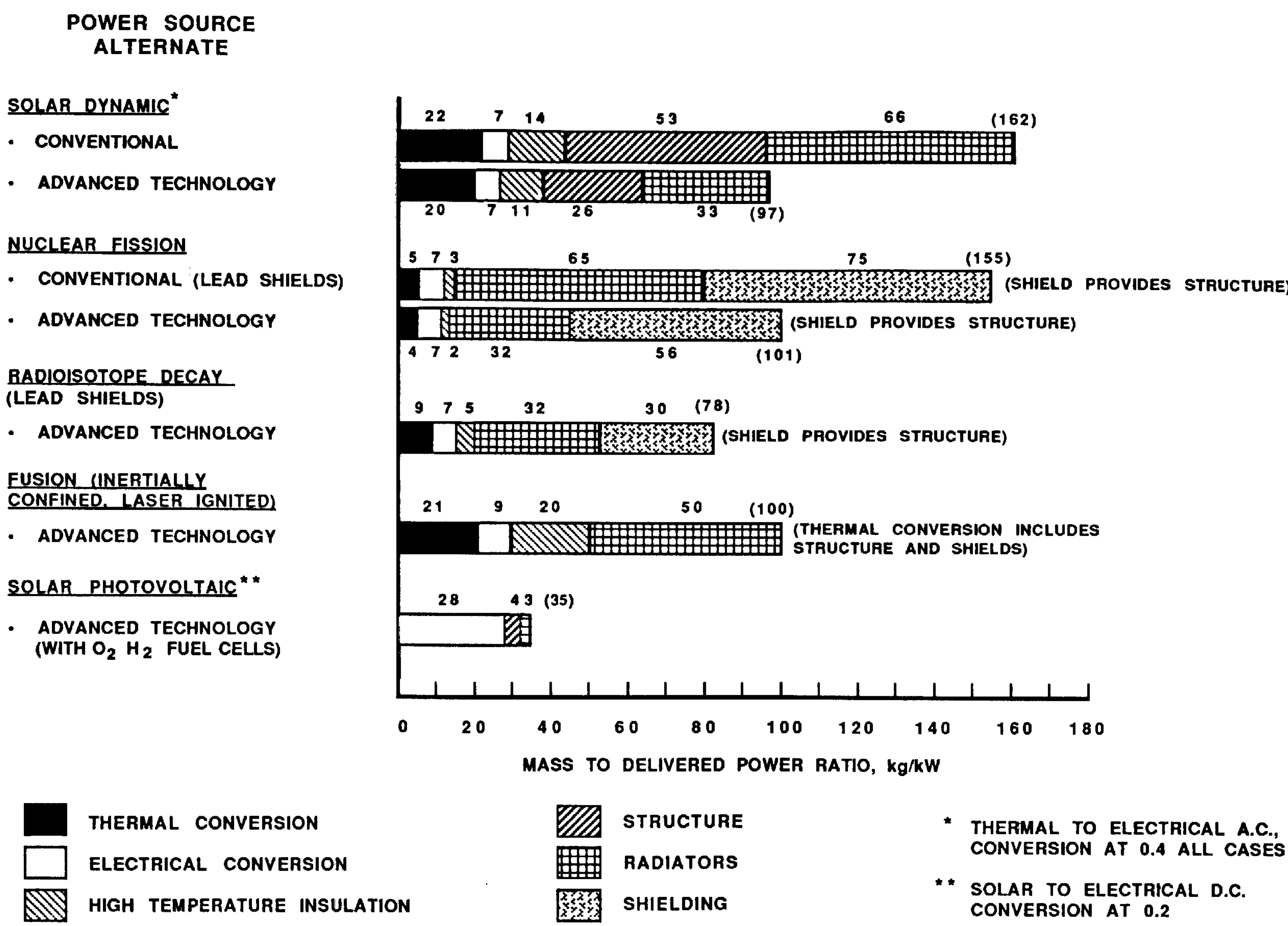


Figure 8-7, Comparison of ATSS Power Systems for Specific Mass Contributions.

mass appear both reasonable and attainable. Shielding is determined by the radioisotope used, and within the candidate isotopes, Pu^{238} has the minimum requirement for radiation shielding. Improved designs for shielding should achieve a 25 percent reduction in mass; the remainder of the system can see some reductions in mass from technical advances. The amount of fuel carried is determined by power requirements, however, improved heat transfer materials and cladding alloys will reduce mass. Improved high temperature insulation will also offer an increment such that radioisotope decay heat sources will continue to have an application to space power systems.

C. Fusion

Radiators appear as the major contributor to total mass for a fusion based system. All fusion system concepts divert a significant portion of their electrical power into internal operations. For the ATSS study, internal requirements become 25 percent with about half utilized to drive lasers. A major portion of the laser power subsequently appears as heat rejection from radiators. High temperature insulation also becomes a significant consideration for fusion based systems. Technology improvements are assumed to reduce thermal conversion elements and high temperature insulation by about 25 percent each, as well as a 50 percent reduction in the mass of the radiators.

D. Solar Dynamic

The solar dynamic system has a significant structural contribution presented by the concentrator, its mountings, collector supports and the collector housing. Advanced materials are assumed to reduce structural mass by 50 percent, the same as for radiators. Mass reduction for thermal conversion elements in the collector and converter has been estimated at 10 percent. However, phase change materials, once selected, remain a fixed mass determined by energy storage requirements.

E. Fission

The practical capabilities for extracting heat generated by fission effectively establishes energy generation densities and the size of a fission reactor core. Energy generation density within the core in turn establishes the intensities of high energy gamma radiation which the shield must absorb by essentially mass-related interactions. The mass of a reactor core and its surrounding insulation can be reduced by improvements in materials, and improvements in radiators can make their contribution. However, the mass for a man-rated radiation shield will remain the largest single element for a fission reactor and the lowest total mass will correlate to use of the most dense material within the shield itself.

8.2 Comparison of Control Requirements

The five systems can be ranked in an order of increasing control complexity based upon considerations that include the number or kinds of control inputs, the range and accuracy required, plus any requirements for cycling.

Solar photovoltaic systems appear to have the least complex control requirements. The principal inputs are measurements of voltage and current. The principal action is switching of sources in sequence with transit through the shadow of the Earth. Within energy storage options, fuel cells would have the most complex controls and be associated with electrolysis of water, handling and storage of H_2/O_2 fuels, and specific operations of the fuel cells. Control requirements for the radioisotope decay system have the next level of complexity. The control system has to operate six closed cycle gas turbines and operate liquid metal pumps which provide heat transfer from the cores. Once stabilized at full power, the system operates at a steady state; cyclic operation would not be required or tolerated in the overall transformation of energy from radioisotope decay.

Controls for solar dynamic systems and the nuclear reactor system appear about equal and are more complex than control for radioisotope decay. Reactor controls must sense neutron distribution within the core and adjust control element positions to maintain power output. In addition, the system will require a continuing monitor for stray radiation to assure a man-rated operating environment. Both the nuclear reactor and the solar dynamic systems have to maintain balanced flows between two liquid metal loops. Solar dynamic units have the complexity of cyclic operation in synchronization with orbit events plus a requirement for precise pointing. Pointing requirements for units on the torus are further complicated by a need for precise solar pointing while rotating. The fusion control system appears as the most complex since it has to maintain a continuing balance of fuel encapsulation, injection, laser firing, liquid metal flow and distribution, plus operation of eight converters. Some fusion control parameters operate with events that require timing in a nanosecond range.

8.3 Other Considerations

The systems can be ranked in an order that reflects operating difficulties or concerns at some point during the life cycle. Photovoltaic panels with a throughput efficiency of 20 percent may suffer thermal damage from solar exposure if they are not connected electrically; therefore, interim electrical loads may be required during assembly and installation. In addition, a 2.5 MW array may expect periodic damage from space debris; as a result, spares and an on-board means for change out appear as a requirement. Solar dynamic units will require an extensive on-board installation and optical alignment of reflecting surface elements that form the concentrator. A lengthy start-up sequence which involves EVA can be anticipated, and an emergency shutdown could damage a unit. At end of life, core components for a nuclear reactor will be intensely radioactive from products of fission and neutron induced reactions. Retrieval of such items has to be performed remotely and requires both the handling equipment and shielded casks needed for storage or transport. The radioisotope decay system generates heat throughout all fuel processing, transport and retrieval operations. A Pu^{238} source decays only 8 percent in ten years. Transport and retrieval from orbit will require some type of a dedicated vehicle. A vehicle which could transport the fuel inventory in 12 trips would evaporate about 5000 kg (11,000 lb) of water duringe each six-hour flight from launch to rendezvous. A fusion system requires substantial electrical power throughout a lengthy start up sequence; therefore a fusion system would need to be an expansion or uprate for an existing on-board power generation capability. In addition, at end of life, the reactor vessel would be radioactive from absorption of neutrons and require both containers and handling equipment similar to those associated with fission reactors.

8.4 Summary and Conclusions

Comparisons of the five systems show areas for required technology advances and make overall assessments of masses required for power generation. An advanced photovoltaic system could provide electrical power at mass ratios below 50 kg/kW (110 lb/kW) using solar cells that achieved a system throughput efficiency of 20 percent, and an advanced storage technique such as Na-Li-sulphur batteries, O_2/H_2 fuel cells, or advanced composite flywheels. Present goals for storage systems appear adequate at 180 W-hr/kg (81 W-hr/lb) for Na-Li-sulphur batteries, 150 W/kg (68 W/lb) for fuel cells and 400,000 N-m/kg (134,000 lb-ft/lb) for composite flywheels. The major required advancement is in long-term system conversion efficiency for solar cells which must be raised by about a factor of three relative to Space Station Freedom and those cells must operate without auxiliary cooling.

The other four systems utilize rotating machinery for electrical conversion. Here, cycle efficiency becomes the parameter that drives both radiator and high temperature heat-transfer requirements. On the Earth, energy conversion efficiencies above 40 percent have been achieved by cogenerating power stations. Present closed-cycle gas turbine systems for space operations operate with thermal conversion effeciencies of about 20 percent. Improvements required will involve some advances in compressors, turbines, and gas-to-liquid heat exchangers. The major portion of the cycle improvements will involve high temperature heat transfer and recovery of waste heat either as regenerators for gas turbines or cogeneration for phase change systems. Any improvements will reduce masses associated with converter portions in each of the systems compared. A solar dynamic system appears capable of producing power for just under 100 kg/kW (220 lb/kW) if masses of the concentrator structure, radiators, and high temperature insulation could be reduced by about 50 percent. These appear as reasonable goals. A reactor-based system will benefit from improvements in high temperature materials and high temperature insulators. An optimized core-shield configuration appears capable of reducing the mass ratio to just above 100 kg/kW (220 lb/kW) by using a dense material (lead, tungsten, etc.) shield. Radiation shields will remain the major mass contribution for any application of nuclear fission reactors.

The radioisotope and fusion systems, while not presently definable, offer attractive features for a space-borne electrical power system. A radioisotope-based system could be brought to a mass ratio below 100 kg/kW (220 lb/kW). If fusion technology resolved the feed, ignition, and energy recovery for a laser-ignited, inertially confined system, then that configuration will benefit from improvements in high temperature materials, high temperature insulation, and radiators.

In conclusion, this comparison shows the technology advances necessary to make each of the systems competitive for a space-borne application and technology areas identified are in active development. The ATSS study served to identify a margin or degree of improvement required. In addition, the ATSS study shows an interdependence within the improvements required. No single technical area can make all the improvements required for optimization. Improved photovoltaics require achievement of development goals for energy storage systems. Higher thermal cycle efficiencies and improvements in radiators benefit all heat source conversion systems. Materials which can perform high temperature heat transfer, and materials with lower density which can provide high temperature insulators also benefit all heat based systems.

Finally the study shows an essential equality for all of the systems. Each system has advantages that can be negated by mission-imposed constraints upon operation. Solar powered systems require both on-board energy storage and precise pointing of large area structures. Mission requirements may not allow either function. Shielding for radioactive sources may not be compatible with mass limits or mass location constraints imposed by mission requirements. In effect, requirements of the spacecraft mission should determine the system selected for generating electrical power.

9.0 ENVIRONMENTAL CONTROL AND LIFE SUPPORT SYSTEM (ECLSS)

The ECLSS aboard the ATSS has to accommodate a 60 person crew for extended periods of time. The ATSS large volume atmosphere must be controlled for temperature, humidity and constituent balance. In addition, the breathing atmosphere requires continuous scrubbing to remove any contaminants. Direct crew-related life support functions, such as food, drinking water, bathing, laundry, etc., must provide continuous support throughout the operating life of the ATSS. These combined requirements establish the need for processes that maximize the recovery of water from waste products and yield a final residue having a minimum need for on-board storage. Human life support requirements are well defined and the ECLSS for Space Station Freedom has addressed each element as part of the overall concept. In context, the ECLSS for the ATSS represents an expansion in scale coupled with an implementation simplified by the presence of artificial gravity. Therefore, the specific functions within the ECLSS for Space Station Freedom and the ECLSS for the ATSS can be directly compared in terms of the method for implementation as seen in Table 9-1. The principal differences appear in recycling of waste water and the means for removing contaminants from the atmosphere. These features are described further in terms of water utilization, recovery of water, waste returned from orbit, and separation of contaminants.

9.1 Water Utilization

An initial design of the ECLSS for Space Station Freedom defined the water usage for the 6 person crew in terms of drinking, food preparation, flushing, hygiene and washing. A water usage flow balance (Reference 1) identified sources of recoverable water, the quantity of water processed by electrolysis and waste products returned to Earth. The ECLSS for the ATSS also received a similar initial definition for water usage (Reference 1), Figure 9-1 makes relative comparison of the two systems for water usage and waste product estimates in terms of kilograms per day for each crew member. The

TABLE 9-1. COMPARISONS OF PRINCIPAL ECLSS FEATURES

FUNCTION	METHODS OR TECHNIQUES USED	
	Space Station Freedom	ATSS
Oxygen Replenishment	O_2 from electrolysis of water	Same
CO_2 Removal	Recyclable molecular absorption	Semi-permeable membranes
CO_2 Reduction	H_2 from Electrolysis of water supply to Bosch Process, H_2O and Carbon	Same
Contaminant Scrubbers	Porous Filters such as Activated carbon	Semi-permeable membranes
Humidity Control	Cold Plate Condenser	Same
Drinking Quality Water	Recovered from humidity condensate and CO_2 reduction	Resupply from stores; Limited recovery from humidity condensate
Urine and Hygiene Waste Water	Chemically treated and filtered, to electrolysis quality and recycled. Solids retained in sludge	Oxidized and solids precipitated. Reclaimed water is recycled, used for trim ballasts and supply to electrolysis
Solid Human Waste	Separated and Returned	"
Wash Water	Chemically treated and Filtered, Recycled	"
N_2 Replenishment	Draw from stored reserve	Partial supply from Oxidizer, remainder from reserves

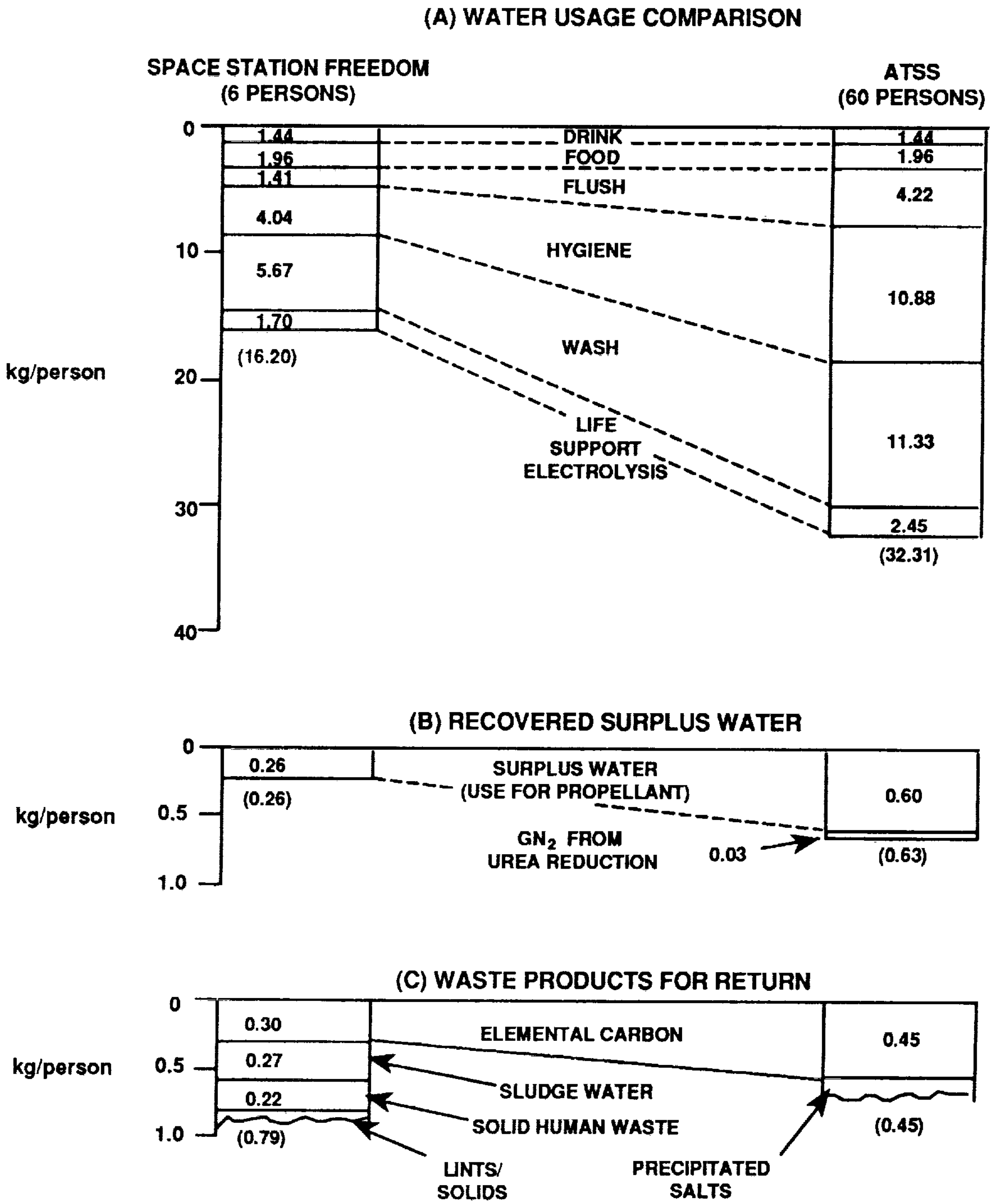


Figure 9-1, Comparison of Daily Water Usage and Waste Products for Space Station Freedom and the ATSS comparisons of water usage use the same values for drinking and food preparation. The ATSS expands the allotments for flushing, hygiene and washing to provide additional comfort. Artificial gravity by rotation allows the comforts of conventional meal service, conventional bathing facilities and laundering of apparel. An expanded utilization of water for crew comfort aboard the ATSS increases the electrolysis requirement by about 40 percent. That additional increment in turn supports a more complete oxidation of waste products.

9.2 Water Recovery

Human metabolic processes oxidize food intakes into water and CO_2 which an ECLSS can eventually recover as extra water. The ECLSS aboard Space Station Freedom makes a direct recovery of metabolic water released into the atmosphere (breathing, perspiration) and recovers the water content from urine by filtration. In addition, the ECLSS reduces atmospheric CO_2 to elemental carbon and water. This degree of closure within the ECLSS provides an amount of excess water available for other utilization, principally electrolysis which generates propellants for station keeping thrusters. A more complete oxidation of waste products results in an even larger amount of excess water. The ATSS concept assumed a wet air oxidation capability that could perform a complete oxidation of carbonaceous materials to CO_2 and water and in addition, could reduce nitrogenous compounds (urea, ammonia, amines, etc.) to the point of releasing gaseous nitrogen. Reduction of all CO_2 to elemental carbon results in the recovery of excess water that more than doubles the quantity otherwise available for propellant generation (or other uses). In addition, the reduction of urea provides some of the nitrogen needed for atmosphere replenishment to offset leakage. Water recovery values shown in Figure 9-1 show the difference between a complete oxidation and the degree of closure proposed for the ECLSS aboard Space Station Freedom. The ATSS recovery value includes the oxidation of all human wastes plus an estimate for additional carbonaceous material in hygiene and wash water as a stearate-based soap. Extra water has an identified use as a propellant for station keeping thrust generation either in a resistojet as for Space Station Freedom or high impulse burning of H_2/O_2 as defined for the ATSS.

9.3 Waste Products Returned To Earth

All ECLSS flows end with a waste product that requires storage and eventual return to Earth. Each crew member aboard Space Station Freedom will show an average daily waste production of about 0.8 kg (1.76 lbs) as elemental carbon, sludge, solids and whatever accumulates in the filters or lint traps. Sludge and solid wastes require special accommodations for on-board storage and handling in the microgravity environment of Space Station Freedom. Complete oxidation incorporated into the ECLSS for the ATSS results in an end product of elemental carbon and inorganic salts for on board storage and eventual return. Neither the carbon nor the salts present particular requirements for containment or handing methods. These comparisons of water usages, recovery of surplus water and waste products show both the advantages and needs for an ECLSS that includes a full oxidation of waste products. An additional increment of electrical power necessary to provide the oxygen appears offset by the extra water recovered and the reduction in end products that must eventually be returned to Earth. The initial definition of the ECLSS for the ATSS proposed wet air oxidation supplemented by vapor compression distillation as the method for waste water processing (Reference 1). Continuing developments in this technology indicate super critical wet air oxidation as a candidate method which can perform the functions of oxidation, nitrogen libration and precipitation of salts within the scope of a single processing sequence (Reference 18). In addition, wet air oxidation releases energy in proportion to the carbon consumed and the water generated during a submerged combustion. This energy becomes available to drive other elements of the ECLSS such as CO_2 reduction or vapor compression distillation. The studies that defined ATSS concepts recognized these potential energy sources and assumed utilization of that energy within the ECLSS. The ATSS electrical power generation of 2550 kW continuous does not include any potential contributions from ECLSS processes.

9.4 Contaminant Separation

Control of CO_2 concentration and the removal of contaminants involve the separation of small quantities from large volumes. The large internal volume of the ATSS leads to the need for an effective and efficient removal method; here application of porous membranes techniques offers an attractive approach. The crew aboard Space Station Freedom will generate about 6.6 kg (14.5 1b) of CO_2 per day, and that quantity in equilibrium throughout the station volume would amount to about an 0.5 percent concentration in the atmosphere. Normal atmosphere shows a concentration of about 0.03 percent, with 1.5 to 2 percent as the upper limit for continuous human exposure. A system that removed CO_2 from the volume of Space Station Freedom each day requires a flow rate of about 11 liters/sec (0.4 ft^3/sec) through the scrubber. The ATSS crew at 60 persons will produce ten times the CO_2 with most of the generation in the two principal habitat sections of the torus. A CO_2 removal system in an inhabited section of the ATSS torus which processed one section volume per day would need a flow rate of 193 liters/sec (6.8 ft^3/sec) through a scrubber and show a CO_2 concentration of about 0.2 percent. An extension of present techniques could provide such a capability; however, the ATSS introduces considerations that favor tailoring scrubbers to both the gasses removed and the specific location. The list of mission functions performed aboard the ATSS includes research laboratories, manufacturing areas, medical facilities, and food preparation areas. Each of these operations can introduce particular contaminants into the atmosphere, such that local filtration and scrubbing appears beneficial for overall control of the atmosphere. In such a system, a separation technique based upon membranes with selected porosities offers the advantage of an extraction technique matched to the local contaminants released. A cascade of membranes appears as a reasonable approach. Present developments in porous membrane technology have indicated such potential capability; renal dialysis filters are well established and reverse osmosis is being applied to water purification. Microgravity fabrication techniques offer the potential for obtaining membranes with porosities that can be tailored to a particular atmospheric contaminant. The ATSS identifies the need for a continuing emphasis in this area of development.

10.0 THERMAL CONTROL

The mission functions performed by the ATSS result in a number of individual heat sources, heat sinks and requirements for local temperature control within the torus, spokes, central tube, and the observatory tubes. These conditions are superimposed upon the overall thermal control for the entire ATSS. Operating features absorb 2550 kW of continuous electrical power while the entire ATSS maintains a stable thermal balance between the incoming solar radiation and heat rejection to space. The elements of the thermal control system for the ATSS include: active temperature regulators; isolators for heat sources and heat sinks; heat pumps and heat exchangers for the internal transfer of energy; and external radiators to maintain the overall balance. Synergy within the thermal control system involves the utilization of rejected heat from high temperature operations as inputs to operations which proceed at the next lower temperature level. Performance levels needed for each of the elements in the ATSS thermal control system establish the corresponding requirements for their technology improvements. Elements for the thermal control system within the ATSS are described in terms of thermal regulators, thermal sources and sinks, heat exchangers and synergies.

10.1 Thermal Regulators

The ATSS operates with a continously varying requirement for thermal regulation by heat transfer into a flowing medium. Electrical power generation provides 2550 kW of continuous energy with up to half (1275 kW) divertable into water electrolysis for load leveling purposes. Therefore the maximum condition for thermal regulation occurs when a thermal load absorbs all available electrical power. A minimum condition occurs when half the power goes to the electrolytic cells. The ATSS has other variable internal heat sources such as heat released by a 60 person crew and exothermic reactions associated with research laboratory operations.

Temperature and humidity control of the cabin atmosphere will present a major requirement for thermal regulation and gas-to-liquid or liquid-to-gas heat exchangers will become the principal control elements. However, the ATSS will also require liquid-to-liquid heat exchangers to accommodate sources and sinks within circulating loops that perform the thermal synergies. The hot loop will draw heat from high temperature operations such as ovens, furnaces, or exothermic reaction chambers and provide heat for dryers, wash water and bathing water. An intermediate loop can accept heat from items such as control panels or power regulators and provide heat for atmospheric temperature control, laboratory chambers, or incubators. A low temperature loop will extract heat from the atmosphere to control humidity and provide a low temperature sink for the other appropriate actions. Areas requiring additional thermal conditioning (such as freezers or cold storage) will operate their heat pumps into one of the two higher temperature loops. Local items of equipment that require temperature regulation (electronics, electrical, etc.) will be designed to maximize their heat fluxes for conditions of minimum mass and size. Actual transfer components, such as heat pipe applications and capillary pumped loops, will always remain a limiting feature and their performance will define the local thermal control capability.

10.2 Heat Sources And Heat Sinks

Equipment aboard the ATSS includes items that must contain high temperatures while either generating or absorbing quantities of heat. Operation of these items will contribute to the thermal balance and thermal synergy. In addition to improved thermal insulation, their operation on-board the ATSS also requires improved heat transfer devices such as heat pipes, and liquid-to-liquid, liquid-to-gas, and gas-to-liquid heat exchangers. The principal heat sources and heat sinks are:

1. Electrolytic cells for the decomposition of water (sources). These units can absorb up to half the electrical power supply from the ATSS and thereby act as the primary load leveling element to a continuous-output electrical power generating system. The units need to operate at temperatures near the one atmosphere boiling point of water and must dissipate heat as determined by their efficiency. Insulation must contain heat generated and some degree of external cooling is required. These units will contribute heat to the high temperature loop.
2. Wet Air Oxidizer (source). These units release the energy of combustion associated with oxidizing carbonaceous wastes and reducing nitrogen to elemental form. Energy released can be converted to supply compressed gases necessary for feed and still have extra energy that can be applied elsewhere. Heat loss must be contained by insulation, and auxiliary cooling will provide a heat input to the high temperature circulating loop.
3. Galley Operations (source). Food preparation aboard the ATSS approximates that for a nuclear submarine. The cooking heat requirements for a 60-person crew has to be supplied and removed. Food preparation ovens and kettles require effective insulation. Liquid-to-liquid heat exchangers must recover heat rejected from scullery operations and minimize heat absorbed by the cabin atmosphere.
4. Bosch CO_2 Reduction Reactors (sink). These units run at elevated (full red) temperatures and absorb the energy necessary to reduce CO_2 to H_2O and C (0.59 kWh/kg, 914 Btu/lb). Electrical resistance provides the heat. The units can operate as part of the electrical load leveling requirement or accept converted energy released from wet air oxidation. Operation at elevated temperatures requires effective thermal insulation to minimize extraneous heat loss.

5. Metal Working Operations (sink). These operations include melting, machining, forming and joining; and all require energy inputs that have to be confined and eventually absorbed. Melting and casting processes have a requirement for high temperature insulation and local heat removal. Conventional machining processes require a fluid which combines the functions of lubrication and cooling. Forming operations such as bending, drawing and swaging also generate heat. Joining operations such as welding or soldering involve a significant heat release. For the ATSS, each operation must be individually considered for thermal control and then integrated into a total system.

6. Composites Fabrication (sink). Lay-up and cure of reinforced polymeric items generally requires a combined pressure and temperature cycle. Operation of curing chambers provides an opportunity for synergy by utilizing heat released from the wet air oxidizer.

The laboratory spaces provided throughout the ATSS will have continuously changing requirements for equipment items which either require and retain heat (furnaces) or generate heat (chemical reactions). Each of the items must be evaluated for thermal control integration.

10.3 Flowing System Heat Exchangers

Efficient exchange of heat between two flowing streams establishes performance parameters for control of atmosphere, extraction of heat from life support functions, and removal of heat from manufacturing operations. The interaction of these heat exchangers combine to establish radiator requirements needed to maintain an overall thermal balance for the ATSS.

Control of temperature and humidity for the cabin atmosphere has to extract water vapor released from a 60-person crew plus all of the energy released into the cabin air from operations throughout the ATSS. Water condensation and recovery implies heat transfer through a chilled surface. The occupied volume of the ATSS and distribution of operations throughout the ATSS identifies requirements for a number of gas-to-liquid heat exchangers which control atmospheric temperature and humidity. The power required to drive circulating fans, circulating pumps and provide refrigeration for coolant loops will be defined by the performance of each heat exchanger in terms of pressure losses and temperature gradients. Each increment of thermodynamic improvement for a heat exchanger yields a corresponding reduction in the required volume, mass and power.

Operation of the life-support related equipment involves transfer of heat through liquid-to-liquid exchangers. Excess heat generated in the electrolytic cells must be transferred into a coolant flow. Operation of the wet air oxidizers involves liquid-to-liquid heat exchange as part of their operating cycle. Both sets of heat exchangers will operate at temperatures which can feed the high temperature circulating loop. In each case, heat exchanger performance influences power requirements for circulating pumps and sizes for the individual exchanger units. The same considerations also apply to fabrication operations where the type of exchangers and their operating sequences are tailored to a particular item or process (e.g., metal working, composite fabrication, etc.).

An external radiator must eventually reject waste heat generated throughout the ATSS and become an active element in a continuous thermal balance. The heat rejected by the radiators will derive from solar inputs, the on-board crew, and the use of electrical power within the ATSS. Rejection requirements also change during dark transit through the shadow of the Earth and vary in concert with energy usage or storage within the ATSS. The shaded section of the torus provides the major area available for thermal balance radiators, and radiator efficiency becomes a significant consideration. The most-shaded quadrant of the torus (45 degrees either side of directly opposite the sun) has an area of 7738 m^2 (83,290 ft^2). A dissipation of 2550 kW continuous would require an average heat flux of 0.325 kW/m^2 (0.028 $Btu/sec\text{-}ft^2$) and correspond to a radiating temperature of 276 K (497° R) or just above the nominal freezing point of water. In actual design, thermal balance radiators will utilize more than one surface operating at more than one temperature with areas and temperatures matched to system needs. Such radiators can utilize any technology advancement that reduces volume or mass.

10.4 Operating Synergies

The circulating loops provide the principal synergy within the thermal control system. Wet air oxidizer provides energy which can be utilized in other operations. Heat energy produced or generated at higher temperatures becomes the heat source for wash water, dryers, laboratory chambers, etc. An intermediate temperature circulating loop provides coolant for electronic and similar operating equipment and becomes a source for local temperature control of living space, laboratory incubators, warming chambers, etc. A low temperature loop provides humidity control and cool storage. Freezers and other heat pumps operate into one of the higher temperature loops such that exterior radiators operate at temperatures which optimizes the power required for thermal pumping against radiator volumes and masses. Technology requirements for the ATSS defined by the thermal control system become an integration for all component operations that will utilize any available improvements in operation of heat pipes, heat exchangers, insulation, heat pumps and radiators.

11.0 COMMUNICATION AND DATA MANAGEMENT SYSTEMS

Requirements for the ATSS communication and data management systems arise from science support functions, spacecraft control operations and relay of data. In addition, on-board assembly and servicing of spacecraft define particular requirements for data storage capacities. The total set of requirements results in systems which must accommodate large quantities of data, both transmitted and stored, with data transmissions and receptions over a wide range of microwave frequencies, plus laser data links for interplanetary distances. A potential operating constraint appears in an expanding need for Earth-used microwave transmission which could fill the allotted frequencies up to 36 GHz (K_a band, Figure 11-1) which are relatively free from atmospheric absorption effects. Earth use priorities could limit some ATSS transmissions. ATSS data links to the Earth will operate with atmosphere-compatible frequencies; however, data links to other spacecraft or companion platforms should anticipate operating in the higher frequency bands that do not overlay or interfere with Earth transmissions. These considerations lead to the concepts and technology requirements for communications and data management which are described below in terms of relays, co-orbit links, Earth transmissions, and on-board elements.

11.1 Relay Communications for Probes and Solar System Exploration

The ATSS offers about half of each orbit period for data relay from distant spacecraft with transmission line-of-sight and unperturbed by the atmosphere of Earth. Laser links are under development for such spacecraft, with a particular emphasis for interplanetary probes. The ATSS will carry laser transmission and receiving elements necessary to provide relay links. Present development efforts address a range of laser wavelengths, a number of data coding techniques, and data rates extending beyond a gigabit per second. The options reflect differences in transmission requirements that exist between a lunar base application and a Neptune probe. Relay communication link

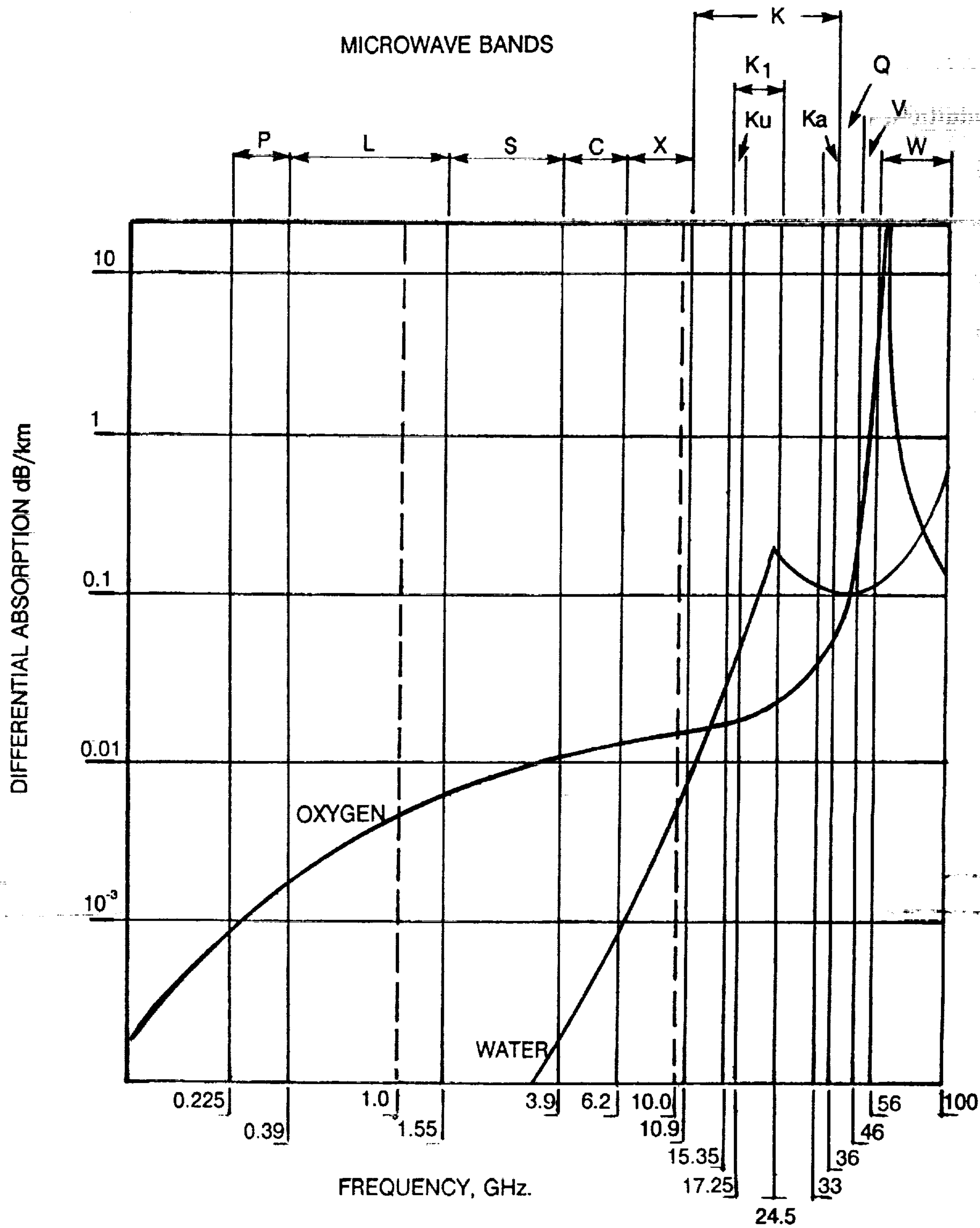


Figure 11-1. Atmospheric Absorption for Microwaves

C-2

capabilities at the ATSS will include laser transmitters, telescope receivers, and microwave equipment that covers the range of communication options available at that time. These link items will operate in conjunction with an on-board capability for data storage and reformatting. Incoming data will need processing for relay to the Earth either as short-term storage or reformatting into an Earth-transmittable form. Development of link and data processing items will respond to the requirements of spacecraft or missions supported by the ATSS. The particular technology requirements pertinent to the ATSS stem from a need for precise pointing and tracking with an emphasis toward laser link operation. Tracking requirements for laser transmitters and receivers are presently defined at one microradian for alignment and 0.2 microradian for line-of-sight jitter. The mounting for laser equipment aboard the ATSS must provide the necessary precision for pointing and tracking over an entire orbit. Laser-transmitted data exchanges with an interplanetary probe requires beam lock as soon as the ATSS emerges from Earth occultation and retention of lock throughout the viewing time. Such requirements become even more critical in support of probes to the outer planets where one-way transmission times exceed the orbit period of the ATSS.

11.2 Communication Links for Co-Orbiting Spacecraft

These communication links operate line-of-sight in the microwave range and the ATSS accommodations would be transmitters, receivers, and antennas (both parabolic and phased array). Antennas have pointing and tracking requirements that involve a continuous movement with changes in direction of motion while maintaining beam-lock. These requirements are supplements to the precision limits defined for laser tracking and introduce the requirement for a "bumpless" transit through a change in direction of motion. The specific equipment items contained in the communication links will be defined from development efforts in support of the particular spacecraft and its mission. High data rates (multi gigabit per second) can be anticipated for links with companion spacecraft, and these links may have need to operate at frequencies above those compatible with Earth transmissions (e.g., the Q,V,W bands or higher, see Figure 11-1). Specific frequency allocations have already been established for spacecraft communication throughout these microwave bands. The particular support required for rendezvous and deployment will include simultaneous operation of a number of microwave links plus lasers for close-approach ranging. These links require real-time data processing and display. Operations will involve unmanned spacecraft or boosters with their attitude control systems responding to commands from control stations aboard the ATSS. Docking and deployment operations with the ATSS will utilize manipulators in the berthing bay, and such operations have to proceed in concert with shifts of trim ballast to preserve the rotating inertial equilibrium of the ATSS. Data processing and display requirements anticipate needs for "giga" operations per second capabilities over short periods of time.

11.3 Earth Communications

Relay satellites provide the continuous communication link between the ATSS and Earth. The maximum data transmission rate becomes the throughput capacity of relay satellites operating in a "bent pipe" mode. The ATSS will have a capability to saturate any relay satellite by multi-channel transmission, and that capability would be available for short-term usage in support of critical functions either on-board or by relay (i.e., a critical phase during the establishment of a lunar base). The general mode of operation will involve on-board processing of data such that Earth transmissions would fill scheduled availabilities for relay links. The ATSS will have the capability for direct transmission (line-of-sight) to stations located on the Earth as part of the accommodations for scientific or science related functions. Such links provide an alternate path for data return and would operate in frequency bands available to the particular user. These links may operate at frequencies assigned to nations other than the U.S.

In summary, the Earth communication links will utilize equipment developed in support of other spacecraft or functions; the ATSS will be their in-orbit host.

11.4 On-Board Communications, Data Management and Storage

On-board systems for communication, data management, and data storage, will support the entire range of functions defined for the ATSS. The maximum rates for data transmission and data reduction are expected during relay operations; the maximum data recording and data storage requirements are expected during spacecraft assembly or servicing operations performed remotely in the berthing bay. In such operations, video recording will provide assembly and inspection records which must be stored as a contingency in support of subsequent flight operations. Actual development of data-processing technology will be driven by other programs of national priority; however, the ATSS will take advantage of any improvements achieved. Table 11-1 summarizes the projected advances for particular features of processing technology. The ATSS can utilize performance parameters that exceed any of the projections listed.

Each operating system aboard the ATSS has specific requirements for control and will respond to inputs from one or more control stations. Table 11-2 lists the control stations for each of the subsystems, and also indicates control redundancies required. In each case, control represents an operating algorithm with a built-in capability for update or special modification to meet particular needs. The on-board configuration of the ATSS will change to meet requirements associated with new scientific investigations, special services to other spacecraft, and to support special items fabricated aboard the ATSS. Each change to the ATSS will have a corresponding requirement for modification to on-board communications, data management, and data storage capabilities.

In summary, communications and data management systems for the ATSS will utilize equipment, concepts, and techniques which were developed for other missions. The principal technology requirement applied to the ATSS is an ability to utilize the capability

TABLE 11-1. ON-BOARD PROCESSING TECHNOLOGY FORECASTS

FIGURE OF MERIT	YEAR AVAILABLE 1985	1990	1995	2000
	ON-BOARD PROCESSORS			
Spaceborne Computers Performance (Mops)	10	40	100	200
Signal Processors Throughput Rate (Mops)	20	100	1,000	----
Microprocessors Performance (Mops)	1	15	30	60
Controller Microcircuit Complexity (gates)	1×10^5	2×10^5	5×10^5	1×10^6
	DATA STORAGE SYSTEMS			
Magnetic Tape				
Capacity (bits)	4×10^{10}	1×10^{11}	3×10^{11}	1×10^{12}
Transfer Rate (bps)	3×10^7	1×10^8	3×10^8	1×10^9
Bubble Memory				
Capacity (bits)	5×10^7	1×10^9	----	----
Transfer Rate (bps)	1×10^6	4×10^6	----	----
Optical Disk				
Capacity (bits)	None	1×10^{13}	----	----
Transfer Rate (bps)	None	1×10^8	----	----
	ARTIFICIAL INTELLIGENCE OR EXPERT SYSTEMS			
Knowledge Base Size (rules)	1×10^3	1×10^4	1.5×10^4	2×10^4
Knowledge Base Throughput (rules/sec)	400	4,000	6,000	8,000
	SOFTWARE PRODUCTIVITY			
Productivity Rate (codelines/man-year)	500	2,500	5,200	8,300

TABLE 11-2. SUMMARY OF CONTROL FUNCTIONS AND TORUS LOCATIONS FOR CONTROL OPERATION

FUNCTION	SPOKE 1	SPOKE 3
A. INTERNAL CONTINUOUS		
1. Electrical Power: Generation, Distribution, Load Management	Primary; All Functions	Partial; Distribution, Load Management
2. Inertial: CG Location, Trim Balance, Rotation	Primary; All Functions	Partial; CG Location, Trim Balance
3. Atomosphere: Temperature, Humidity, O_2 Replenishment, CO_2 Removal and Reduction	Primary; All Functions	
4. Wastewater Collection and Reclamation	Primary; All Functions	
5. Gas Management: Propellant Generation, Storage, Ullage	Primary; All Functions	Partial; Fuel Transfer
6. Internal Communciation:	Primary	Duplicate
7. Station Keeping	Primary	Duplicate
B. INTERNAL SUPPORT FUNCTIONS		
1. Central Tube Manipulators	Primary	Duplicate
2. Microgravity Operation	Primary	Duplicate
3. Solar Observatory	Primary	Duplicate
4. Astronomoical Observatory	Primary	Duplicate
5. Earth Science	Primary	Duplicate
6. Horticulture	Primary	Duplicate
7. Variable Gravity	Primary	Duplicate
8. Elevator and Transfer	Primary	Duplicate
9. EVA Operations	Primary	Partial; Non-Rotating

TABLE 11-2. SUMMARY OF CONTROL FUNCTIONS AND LOCATIONS FOR CONTROL OPERATION. (concl.)

C. EXTERNAL SUPPORT FUNCTIONS	SPOKE 1	SPOKE 3
1. Communications: Relay, Earth, Beyond Earth Orbit	Partial; Relay and Earth	Primary
2. Tracking	Partial; Berthing Functions	Primary
3. Energy Relay		Primary
4. Berthing: Berth, Equipment Transfer, Service Using Manipulators	Partial; Transfer or Service	Primary
5. Companion Spacecraft Operations		Primary
6. Airlock Operations	Duplicate	Primary

presented. The requirements include a particular capability to provide precise pointing and tracking controls associated with laser communication links and continuity for communication locks during rendezvous or deployment operations.

12.0 MARS MISSIONS AND LUNAR BASE SUPPORT

The ATSS has the capability for logistic support to planetary and lunar missions. Particular support functions include: accommodation for the work force during assembly of mission vehicles; accommodation for planetary and lunar crews before departure and after return to LEO; a large spacecraft berthing and assembly bay with supporting cranes; machine shop capability for on-orbit fabrication of parts; and a capability to store and transfer propellants. In addition, the ATSS has the capacity to produce quantities of H_2 and O_2 for propellants.

Proposed manned missions to Mars (References 19 and 20) were reviewed for specific impacts on the design of the ATSS. These missions presented operational requirements such as assembling nuclear power sources in LEO, handling large amounts of cryogenic propellants, and supporting OTV operations for departures from high Earth orbit (HEO). The ATSS could accommodate such missions; Figures 12-1 and 12-2 show a conceptual Mars mission vehicle docked within the berthing and assembly bay. The particular vehicle shown uses chemical propulsion and aerobraking at both Mars and upon return to LEO. The ATSS can be the LEO staging site during Lunar base construction and operation. These operations show a need for 800 metric tons of equipment delivered to the lunar surface over a period of 10 years (Reference 21). Transport of such equipment to the lunar surface will consume propellants with most propellants delivered to and handled by the ATSS. Chemical propellants can be cryogenic, hypergolic (or both) in quantities greater than the mass of the equipment transported. A permanent crew of 18 persons on the lunar surface also will involve a rotation among an additional number of individuals. Each person would spend some period of time aboard the ATSS during transport operations from the Earth to the Moon and return.

In summary, Lunar and Mars missions support requirements and interactions were incorporated into the ATSS configuration. Table 12-1 summarizes the principal requirements and interactions identified; all appear within the range of ATSS responses.

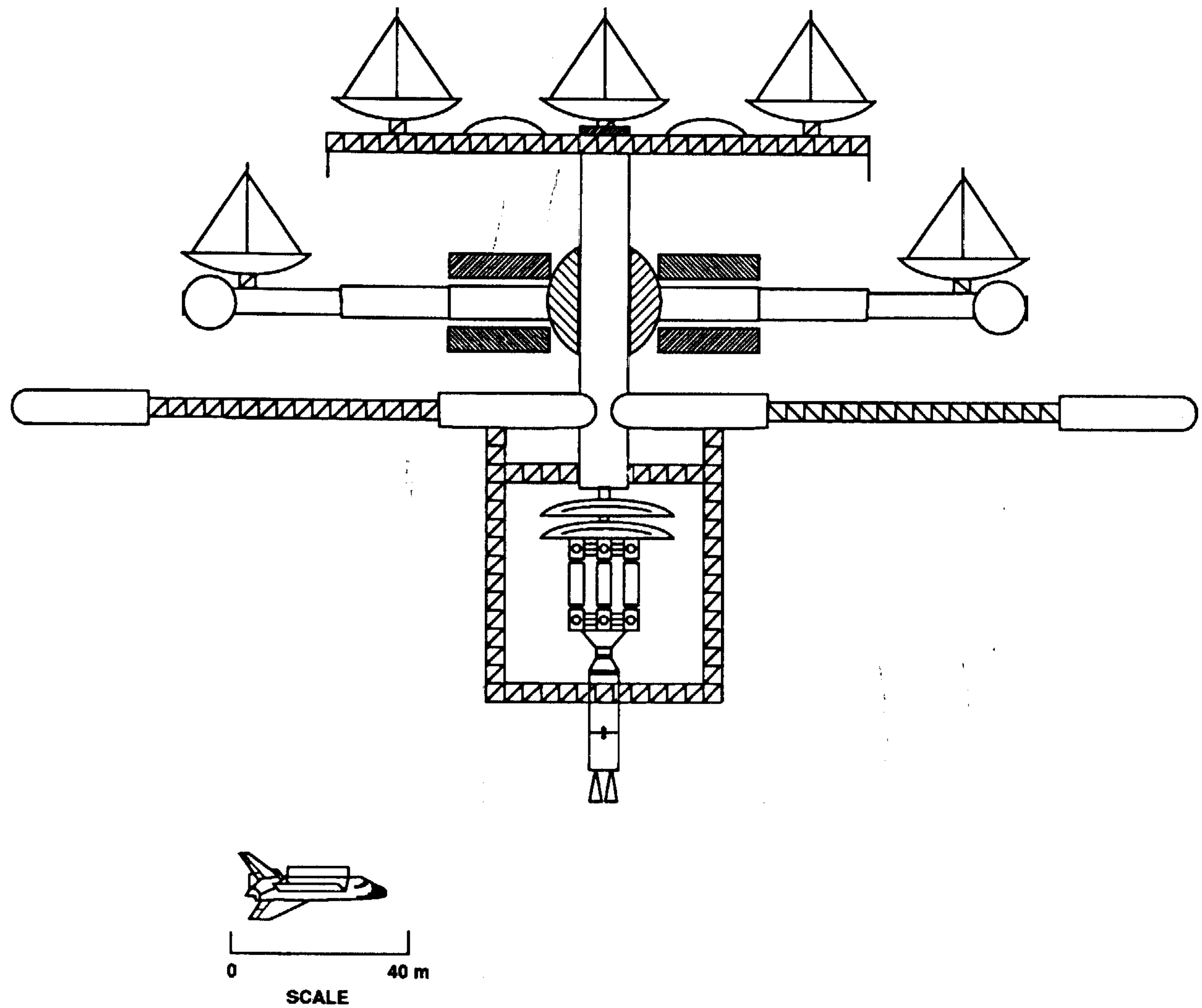


Figure 12-1, Assembly and Service of a Mars Probe Within the Berthing Bay of the ATSS.

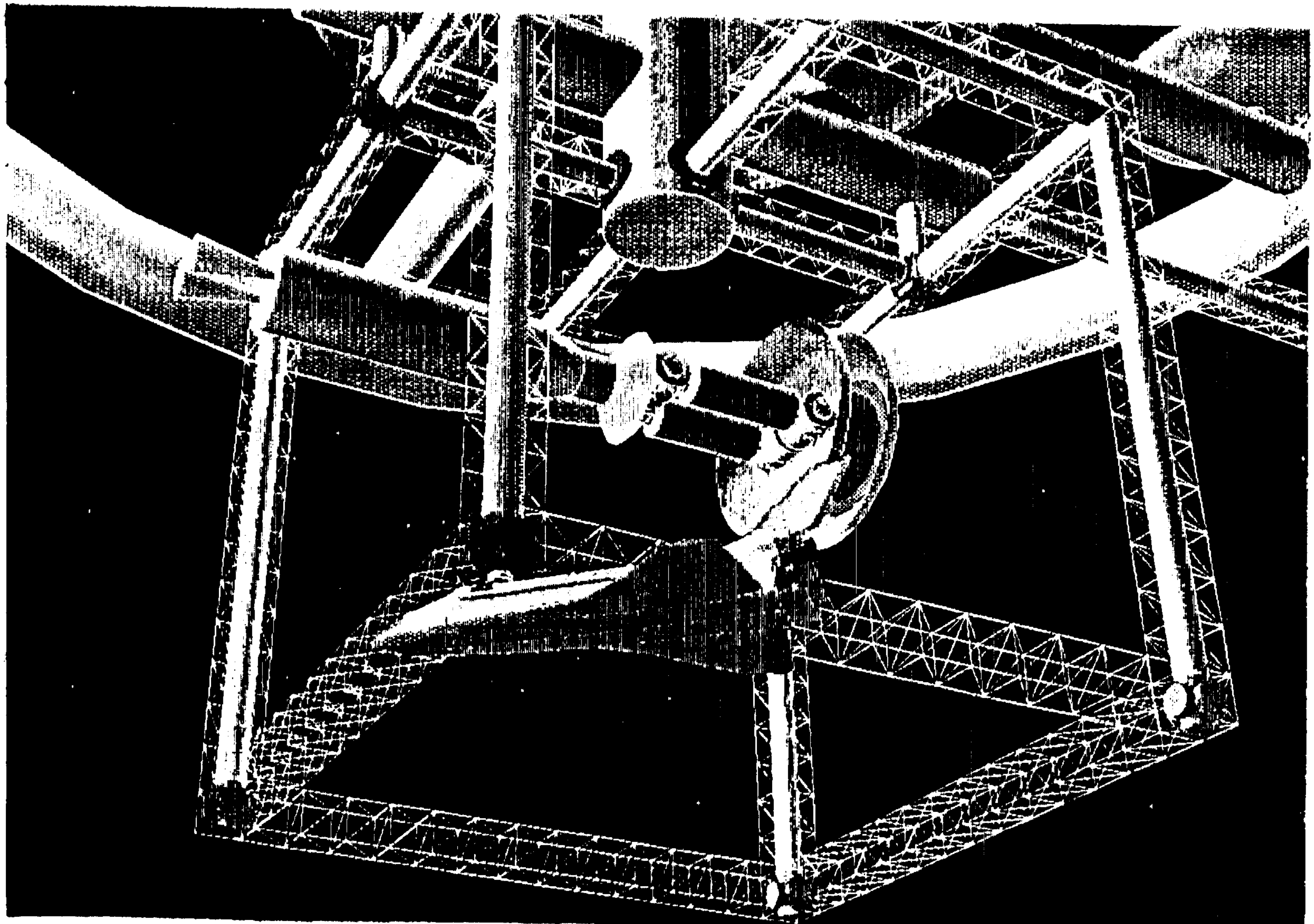


Figure 12-2 Concept for Servicing a Mars Probe Within the ATSS Berthing Bay Drawn Using the IDEAS² Program

TABLE 12-1. LUNAR AND PLANETARY MISSION REQUIREMENTS FOR THE ATSS

MISSION REQUIREMENT	ATSS IMPACT
Delivery to ATSS of mission related hardware, crew, and supplies from Earth	• Frequency of HLLVs, shuttles, aerospace planes or other vehicles to dock and service
Delivery to ATSS of propellant needed for mission support	• Propellant handling • Propellant storage o Possible nuclear or fission fuel handling
Propellant production on-board ATSS for mission spacecraft	• Delivery of H_2O from Earth followed by H_2 and O_2 production on the ATSS • Cryogen facilities on ATSS to liquify and store fuels
Assembly at ATSS of mission spacecraft	• Component assembly in torus or central tube • Assembly in, or attached to, the berthing bay • Assembly of spacecraft in companion orbit
ATSS controllability effects	• Docking accessibility of other vehicles during mission spacecraft assembly • Interconnections between the ATSS and mission spacecraft; air locks, power, fluid exchanges, thermal control systems, communications
Operational support by ATSS	• Delivery of Crew to HEO after unmanned spacecraft traverse through Van Allen radiation belts • Quarantine facilities and sample processing on ATSS for sample returns o Lunar sorties of OTVs supporting a lunar base buildup (~14 sorties per year for 10 years) o Machine shop and other facilities which support recovery of spacecraft that otherwise would be returned to Earth or scrapped

13.0 SUBSYSTEM SYNERGISTIC INTERACTIONS

The initial definition for ATSS emphasized concepts that involved synergistic interactions between subsystems. As the studies continued, some of the original synergies became operating necessities, particularly those synergies associated with generation of electrical power and attitude control requirements for a Sun-facing orbit. The descriptions below identify potential synergistic interactions and describe pertinent considerations that makes multiple use of water an operating necessity.

13.1 Synergies Identified

Potential synergies within the ATSS are listed in Table 13-1. The listing begins with a need for electrical load leveling, then identifies multiple uses of water and concludes with synergies related to specific subsystems. All potential synergies have been mentioned in earlier descriptions and discussions of subsystems, such as previous Sections 3 through 12, or References 1 through 4 inclusive.

13.2 Required Synergies: Multiple Utilization of Water

The evaluations of alternate methods for ATSS electrical power generation and the continuing analysis of orbit related dynamic effects identified operational requirements that made multiple utilization of water necessary. Solar powered electrical generation systems require both a Sun-facing orbit and a means for storing energy. Electrical power must continue during transit through the shadow of the Earth; as a consequence, solar-powered electrical generating systems aboard the ATSS became single-point continuous operations. Power system equilibrium operations dictate that solar energy must be absorbed and stored energy recovered within the cycle of each orbit. Electrical load leveling therefore becomes a necessity, and electrolysis of water provides such a capability. Alternate power sources based upon some form of nuclear heat generation eliminate the need for energy storage but not the need for load leveling.

TABLE 13-1. POTENTIAL SYNERGIES IDENTIFIED FOR THE ATSS

A. ELECTRICAL POWER LOAD LEVELING OR LOAD MATCHING (APPLICATION OR SCHEDULING OF POWER)

1. Excess power diverted to the electrolysis of water.

2. Excess power directed to compression of gasses for liquification or high pressure storage.

3. Power scheduling to accommodate mass transfer from non-rotating to rotating section and operation of the elevators.

4. Power scheduled or excess power directed to transfer of water into the torus, along with electromagnetic torquing to build up inertia in response to a transfer requirement.

5. Schedule for wet air oxidation operation.

6. Schedule for gas transfer operations.

7. Schedule for CO_2 reduction.

8. Balance the usage of electrical power and chemical power for solar-facing precessions.

9. Schedule for the on-board fabrication operations.

B. SYNERGIES FOR THE UTILIZATION OF WATER BY SCHEDULE OR FLOW SEQUENCE

1. Center of gravity control during berthing and deployment, by transfer of water ballasts.

2. Movement of water into rotating sections during materials transfer.

3. Utilization of water for inertial null by the counterrotators.

4. Water transfer to the torus during elevator operations.

5. Water transfer for trim balance of rotating section in response movement of equipment and personnel within the torus.

6. Fresh water utilization for drinking and food preparation, then reclaimed.

7. Reclaimed water utilized for flush, clothes wash, and housekeeping and then recycled.

8. Reclaimed water utilized for trim ballast.

9. Reclaimed water feed to electrolysis for O_2, H_2 generation.

10. Reclaimed water utilized as gas turbine precooler radiator coolant for power generation convertors.

TABLE 13-1. POTENTIAL SYNERGIES IDENTIFIED FOR THE ATSS (concl.)

C. SYNERGIES PRESENTED BY ON-BOARD GENERATED GASSES

1. Cabin air as ullage gas for O_2.
2. N_2 and CO_2 as ullage gasses for H_2.
3. O_2, H_2 utilization as needed for life support and propellants.
4. O_2, CO_2, N_2 as atmosphere constituents for horticultural research.
5. N_2 recovered from waste stream water by super critical wet air oxidation.

D. SYNERGIES PRESENTED BY STRUCTURE AND CONSTRUCTION

1. Assembly manipulators become berthing-bay units.
2. EVA mobile crane initially supports construction and assembly.
3. Observation tube and berthing-bay tubes serve as air reservoirs for central tube air lock operations.
4. Raw stock for on-board fabrication retrieved from supply spacecraft materials.

E. SYNERGIES WITHIN SUBSYSTEM OPERATIONS

1. Waste heat from high temperature sources recovered as sources for lower temperature operations.
2. Counterrotators plane of rotation has controlled cyclic changes to null gravity gradient torque.
3. Focused solar beam from solar dynamic concentrators provides high temperature source for research experimentation.

A spacecraft in a Sun-facing attitude will experience gravity gradient induced torques which are cyclic and occur at two times the orbital frequency (See Sections 6 and 7 above). The magnitude of the torque is determined by the dimensions, the mass and the mass distribution within the spacecraft. Gravity gradient effects cited for the ATSS require large rotating masses for an effective countermeasure. The rotating portion of the ATSS is in itself a large gyroscope, and for a Sun-facing orbit the plane of rotation for the torus must precess at one revolution per year. Counterrotators that null the gyroscopic forces facilitate that precession and also appear as the practical means for counteracting gravity-gradient torques. Therefore, the ATSS has to carry a counterrotating ballast that cancels the gyroscopic effects and counteracts the gravity gradient effects by small changes in the plane of rotation. Ballast requirements are large, and water presents the practical material. In recognition of these requirements, water then provides the synergy of functions such as ballast, as a heat transfer medium, as liquids for life support and crew comfort and eventually, as gasses for both life support and propellants. Water from Earth moves through the ATSS in a series of steps and uses; Figure 13-1 shows the usages and their interactions. Fresh water delivered to the ATSS is initially used for ballast and the counterrotators provide the reservoirs. Water then moves into the torus for crew usage and other applications. Wastewater, reclaimed by an oxidation process, provides local trim ballast before eventual decomposition into gasses for life support or propellants.

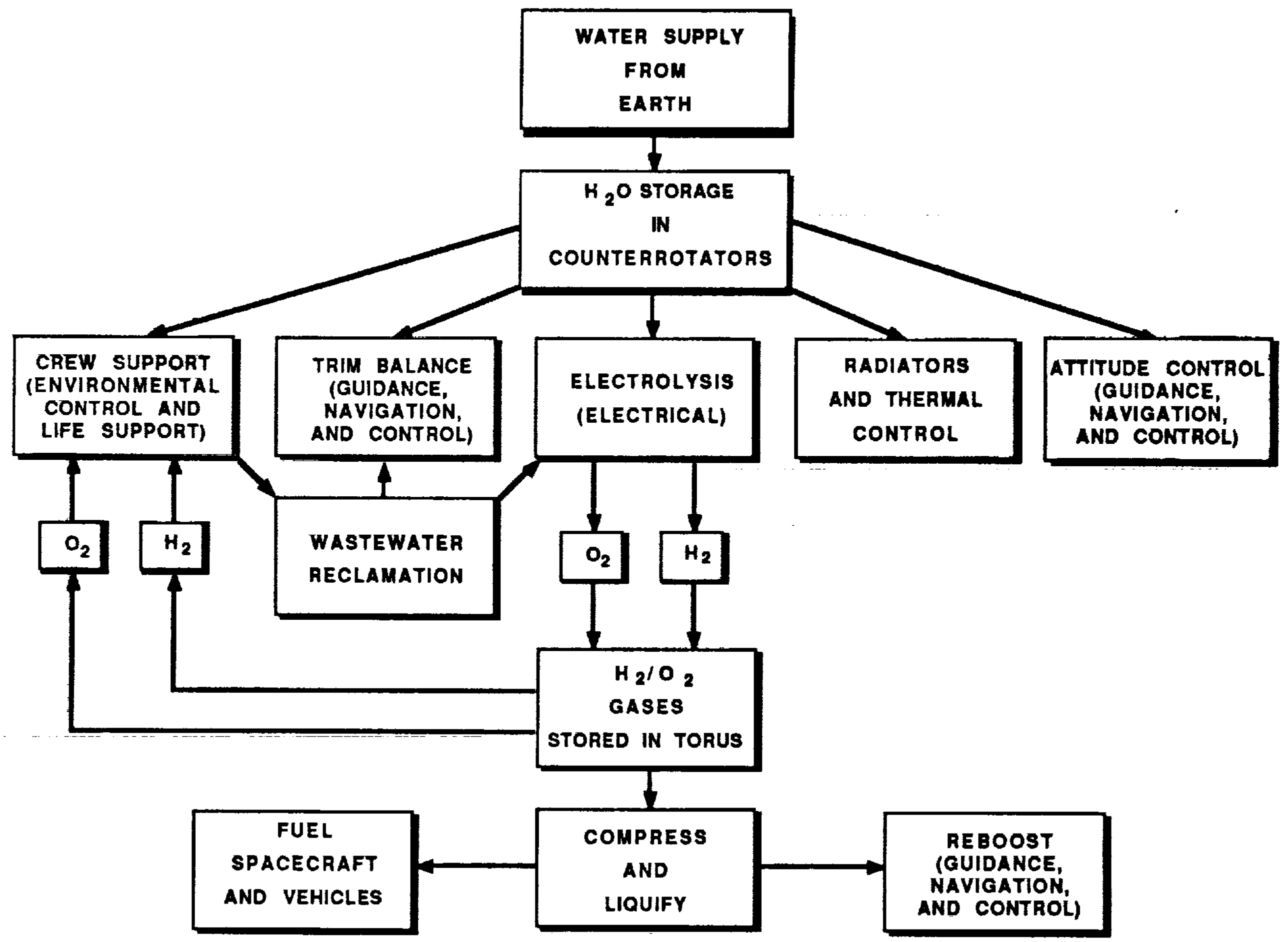


Figure 13-1 Summary of Water Utilization Aboard the ATSS

14.0 ADVANCED TECHNOLOGIES IDENTIFIED

The concepts for the ATSS specifically addressed definition of technology requirements and identification of major technical issues pertinent to long-term, multipurpose space vehicles which operated with artificial gravity by rotation. The descriptions of the ATSS, definitions of subsystems, and continuing evaluation studies combined to identify 21 technology advances or technical definitions required to implement an ATSS by the year 2025. The 21 technology items can be grouped into 5 general areas as follows

Structures, Materials and Mechanisms (9 items)

Environmental Control and Life Support (2 items)

Attitude Control and Station Keeping (4 items)

Electrical Power Generation and Thermal Control (2 items)

On Orbit Assembly and Transportation (4 items)

These technology areas are addressed below in terms of critically, readiness, application, and potential benefits.

14.1 Technology Ranking for Criticality and Readiness

Each technology item has been ranked for criticality and readiness. Ranking criteria for criticality appear in Table 14-1 using a scale of 1 to 10; readiness criteria appear in Table 14-2 using a scale from 1 to 7 and these are the same as for other NASA forecasts (Reference 6). The 21 technology items with ranking assessments are listed in Table 14-3. Criticality criteria reflect the ATSS need or dependance; a criticality ranking below 7 indicates an availability of alternative approaches at some sacrifice in ATSS performance or capability. Criticalities from 7 through 9 inclusive are considered to offer little in the way of alternatives, and rankings of 10 are ATSS specific. The readiness criteria were established to support other NASA-sponsored studies. When applied to the ATSS, higher readiness estimates identify technologies that are operational

TABLE 14-1. ATSS TECHNOLOGY CRITICALITY RANKING CRITERIA

The technical advance will enhance performance; alternate means exist.	1 2
The technical advance will define the performance; alternate means would limit performance.	3 4
The technical advance is required for subsystem operation; reduced performance compromises other subsystems.	5 6
The technical advance is required for subsystem operation.	7 8 9
The ATSS cannot be configured without this capability.	10

TABLE 14-2. ASSESSMENTS OF TECHNOLOGY READINESS (Reference 6)

Level 1 -- Basic principles observed and reported

Level 2 -- Conceptual design formulated

Level 3 -- Conceptual design tested analytically or experimentally

Level 4 -- Critical function or characteristic demonstrated

Level 5 -- Component or breadboard tested in relevant environment

Level 6 -- Prototype or engineering model tested in relevant environment

Level 7 -- Engineering model tested in space

TABLE 14-3. SUMMARY OF TECHNICAL ITEMS IDENTIFIED FOR THE ATSS WITH ASSESSMENTS OF CRITICALITY AND READINESS.

	TECHNOLOGY	CRITICALITY	READINESS
A.	Structures Materials And Mechanisms		
1.	Expand structural design and analysis capability for large units fabricated with advanced materials using new techniques.	7	4
2.	Develop large filament reinforced structural composites.	6	4
3.	Develop expandable and modular structural concepts that can perform as part of ATSS.	6	4
4.	Develop low mass industrial equipment.	9	3
5.	Define the artificial gravity environment. - Experimentally verify a gravity acceleration compatible with long term human operations. - Develop the control algorithms and methods necessary for sustained rotational operation.	10	2
6.	Define internal operating atmosphere contents and pressure. - Verify human compatibility. - Verify equipment compatibility.	4	5
7.	Develop large articulated airlocks, doors, and seals compatible with the ATSS.	9	3
8.	Develop large diameter rotating joints and their rotational drives.	10	2
9.	Develop large diameter gas seals.	10	2

TABLE 14-3. SUMMARY OF TECHNICAL ITEMS IDENTIFIED FOR THE ATSS WITH ASSESSMENTS OF CRITICALITY AND READINESS (cont'd).

	TECHNOLOGY	CRITICALITY	READINESS
B.	Environmental Control and Life Support		
10.	Develop ECLSS components with 10 year operating life and maximum closure or recovery in air, water and waste cycles.	8	3
11.	Provide an improved ability to remove contaminants from the atmosphere and water.	8	3
C.	Attitude Control and Station Keeping		
12.	Develop new techniques for momentum storage and momentum control.	8	2
13.	Develop algorithms to predict the dynamics and control requirements for large space vehicles with flexible rotating and articulating elements.	7	5
14.	Configure intermediate range (500 N - 5000 N) thrusters with contaminant-free exhaust products.	7	5
15.	Develop the algorithms required for autonomous operation in-orbit.	7	3
D.	Power Generation and Thermal Control		
16.	Develop high specific power electrical generating systems.	7	4
17.	Improve the performance of thermal control devices and radiators.	6	4

TABLE 14-3. SUMMARY OF TECHNICAL ITEMS IDENTIFIED FOR THE ATSS WITH ASSESSMENTS OF CRITICALITY AND READINESS. (concl.)

	TECHNOLOGY	CRITICALITY	READINESS
19.	Develop on-orbit assembly methods for ATSS sized elements (position, align, join, verify).	10	2
20.	Develop high mobility, no prebreath space suits compatible with operation in a rotating environment.	7	6
21.	Provide heavy lift launch vehicles with a nominal capability of 270,000 kg delivered to orbit.	9	6

on smaller scale spacecraft or launch systems. Such an example appears in Heavy Lift Launch Vehicle required for the ATSS. The Saturn V booster was made operational for a payload capability about half the capacity needed for ATSS support. In addition, presently available main engines in the shuttle are operational in the thrust range needed for an HLLV application. Therefore, HLLV's of the size identified for ATSS are considered within present technology and would need only the commitment of resources for accomplishment.

14.2 Technology Considerations

Technology requirements, have been addressed in the system descriptions of sections 3 through 12 above and References 1 through 4. The comments which follow clarify applications or provide a rationale for inclusion within that particular group.

A. Structures, Materials and Mechanisms.

The rationale and benefits from developments of advanced materials and structures appears in Section 5. The first three areas of technology identify particular analytical methods and structural advances required for the ATSS and these advances would apply to any large space vehicle. A need for low mass industrial equipment arises from extended living in space as well as fabrication operations. Efforts are underway to provide higher-power, low-mass electric motors. However, the equipment they drive, such as pumps, fans, compressors and machine tools also need equal attention.

Considerations for artificial gravity level and internal operating atmosphere will involve research and experiments performed by other disciplines. However, for the ATSS, their impacts are structural in terms of loadings imposed by centripetal accelerations and material stresses due internal to pressures. The last three technology items are pertinent to large internally pressurized spacecraft which have both rotating and non rotating sections, and these items are configuration-critical for the ATSS.

B. Environmental Control and Life Support Systems

The assessments of performance requirements for the ECLSS items have been addressed in Section 9 above. The system definition study assumed a 10-year life requirement. However, a space vehicle of ATSS size would have an operating life of much longer duration. The 10 year period may be considered a required continuous operating time between system updates or change out.

C. Attitude Control and Station Keeping

These technology requirements apply to all large space systems. The degree of complexity correlates to the source of electric power and requirements for attitude stabilization during orbit. A gravity gradient stabilized structure with an internal power source would show minimum need. Power from solar sources introduces requirements for articulation and pointing. A rotating, Sun-facing ATSS addresses the most complex condition. The need to transfer operational control from ground to orbit begins when an orbiting facility becomes a control and communication center for other spacecraft. In this case, the listing of functions to be performed aboard the ATSS precludes any other than an on-board flight control.

D. Electrical Power Generation and Thermal Control

Availability of electrical power and requirement for thermal control are critical elements for all space vehicles. Comparisons of alternate electrical power generation systems summarized in Section 8 above, have identified pertinent areas and items requiring development. The need will continue for more on-board electrical power produced with minimum mass delivered to orbit. Assessments of thermal control elements as summarized in Section 10 above also show a continuing need for improvements that accomplish heat transfer and thermal regulation with a lower power demand and less mass delivered to orbit.

E. Assembly and Transportation

The considerations pertinent to these technology requirements are described in Section 5 above. These items also apply to all large space vehicles. The robotics and assembly methods address a scale in size and mass well beyond the limits associated with Space Station Freedom. The need for an immediate-use space suit has been identified for Space Station Freedom, and other advanced concepts have been defined. In this area, the ATSS adds the unique requirement for operating in a rotating environment.

14.3 Assessments of Identified Technology Advances

The 21 technology areas identify some advances in which the accomplishment itself contains the benefit. Items such as the development of robotics, assembly methods, rotating joints, rotating seals and methods for momentum control appear as achievements that become enabling precursors to an ATSS. In other areas, the ATSS requirements are milestones in a continuous development of capability, such as for electrical power generation and thermal control devices. Identified beneficial synergies exist between technological advances, such as use of electrolysis for electrical load leveling to produce gasses for both atmosphere replenishment and propellants. Within these interactions, effects can combine in a manner that shows additional benefits.

15.0 TECHNOLOGY EFFECTS AND INTERACTIONS

The ATSS study examined the potential effects and interactions of advanced technologies on both system operations and mass delivered to orbit. Examples of significant benefits and interactions appeared in the case where advanced composite structural elements could be utilized in conjunction with operations at a reduced artificial gravity and a reduced internal pressure. For these evaluations, the effects of advanced composites was averaged at a 30 percent reduction in mass relative to aluminum construction (Section 5), the artificial gravity level was selected at 0.5 Earth and the internal atmospheric pressure established at 70 percent of sea level standard. The evaluations and comparison examples consider.

a. Relative reductions in mass delivered to orbit as fractions (percent) of the baseline value for the rotating and stationary sections without consideration of counterrotators.

b. Estimates of mass to orbit reductions for the baseline ATSS considering the interactions with the counterrotators.

c. Estimates of mass to orbit reductions if the artificial gravity changes are accomplished by a change in the diameter of the rotating torus.

All three comparisons relate to the baseline definitions of the ATSS as shown in Figures 3-2 and 3-3.

15.1 Baseline Definition of the ATSS

The baseline ATSS assumes conservative aluminum based structure similar to that proposed for Space Station Freedom. For convenience, the estimate of masses can be addressed as three major assemblies; rotating, which includes the torus spokes hub and two solar dynamic units; stationary, all the items inertially fixed and the counterrotators. The masses within the rotating and stationary sections are each considered as the sum for the following elements:

a. Pressure Shells: Structure with the principal loading defined by the internal atmospheric pressure.

b. Structure: Internal elements such as floors, walls, and tie beams. These units support the centripetal force "gravity" loads within rotating elements.

c. Equipment: Items mounted on floors, walls etc. These items provide the operating capabilities within the ATSS.

d. Atmosphere: The gas quantity within the habitable areas maintained at breathable quality.

e. Variable: Crew, supplies, trim ballast and consumables. These are assumed constant for this comparison.

f. Power: Six identical solar dynamic units delivering 2550 kW continuous at a specific power of 100 kg/kW and assumed constant for this comparison.

These elements also include two further simplifying assumptions, first, the torus, spokes hub, central tube and other inhabitable volumes all have the same internal atmosphere and pressure. Second, the equipment, structure, and variables are distributed uniformly throughout the rotating section.

The masses for each of these elements have been drawn from the initial estimates (Reference 2) and they are summarized in terms of metric tons as the first column of Table 15-1 (Aluminum Materials, Earth Gravity, Standard Atmospheric Pressure).

15.2 Relative Effects Comparison

The masses calculated for each of the elements within the rotating and stationary sections make proportionate contributions to the total mass for the two sections, Figure 15-1 summarizes the contributions from each of the elements as a percent of the total. The baseline configuration for the ATSS shows 68 percent of the mass in the rotating section and 32 percent of the mass in the stationary section, with the pressure shells in the rotating section as the largest single contributor at 30.8 percent. These relative

TABLE 15-1. EFFECTS OF MATERIAL AND ENVIRONMENT CHANGES ON MASS OF THE ATSS FOR A TORUS RADIUS OF 114.3 METERS. (Masses are in Metric Tons)

Defining Parameters	Aluminum Materials Earth Gravity Std. Atm. Press.	Composite Materials Earth Gravity Std. Atm. Press.	Composite Materials 0.5 Earth Gravity Std. Atm. Press.	Composite Materials 0.5 Earth Gravity 0.7 Std. Atm. Press.
ATSS Without Counterrotators				
Rotating Sections				
Pressure Shells	1294	906	906	634
Structures	748	524	272	272
Equipment	307	215	215	215
Atmosphere	223	223	223	156
Variables	197	197	197	197
Power	88	88	88	88
Total	2857	2153	1901	1562
Stationary Sections				
Power	185	185	185	185
Variables	113	113	113	113
Atmosphere	46	46	46	32
Equipment	197	138	138	138
Structures	454	318	318	318
Pressure Shells	349	244	244	171
Total	1344	1044	1044	957
Total ATSS Without Counterrotators	4200	3197	2945	2519
Counterrotators	4300	3236	2053	1685
Total ATSS	8500	6433	4998	4204

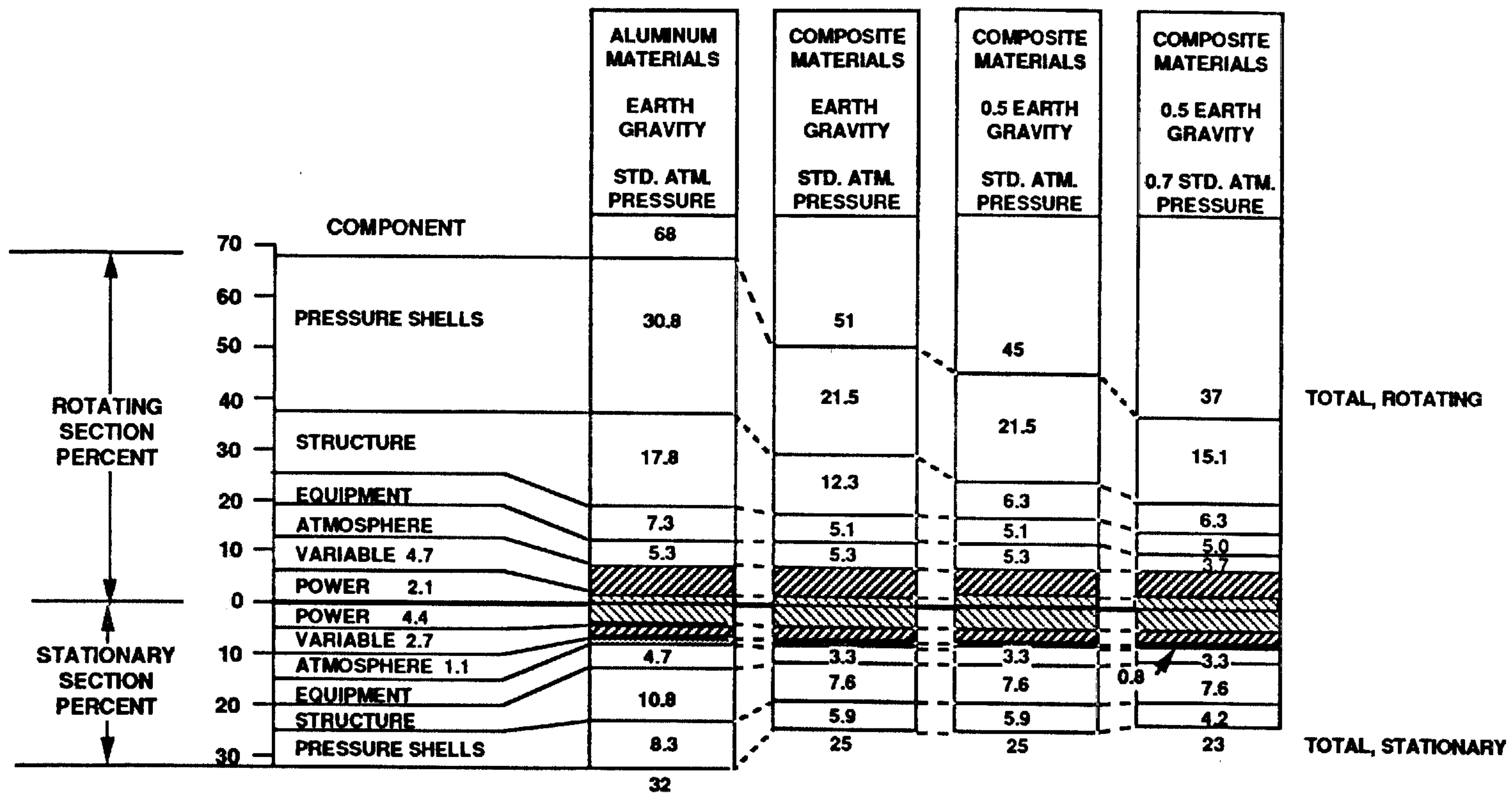


Figure 15-1, Effects of Technology and Technology Related Definitions Upon the Relative Masses of Major ATSS Components.

contributions become the basis for comparing the effects of advanced composites, reduced artificial gravity and reduced internal pressure.

A. Effects of Advanced Composites Technology

The assessments of advanced materials technology presented in Section 5 above shows the potential for mass reductions ranging from 15 to 47 percent relative to conventional aluminum structure. Within the mass contributions to the ATSS, advanced composite materials would apply to pressure shells, structure and equipment (Technology Items 1 through 4, Table 14-1). If the application of advanced composite materials within the ATSS yielded an average mass reduction of 30 percent, the resulting values become those listed in column 2 of Table 15-1 as Composite Materials, Earth Gravity, Standard Atmospheric Pressure. The relative contributions from each element are summarized in Figure 15-1 and show the distribution listed under Composite Materials, Earth Gravity, Standard Atmosphere. The application of advanced materials reduces the total mass for these sections by 24 percent with 17 percent of the improvement in the rotating section.

B. Effects of Reduced Gravity

A partial gravity level compatible with long-term human operation in space has not been defined. If research data indicates that reduced-gravity levels can be tolerated, some reductions in ATSS mass are possible. A gravity of one half of the Earth value will quantify the possible benefit. Mass reductions are measured relative to the ATSS using advanced structures and operating at a 1-g level. For this comparison, the reduction in artificial gravity allows a reduction in the torus rate of rotation from 2.8 to 2.0 rpm. A direct benefit of reducing the artificial-gravity level is the reduced effective weight of the equipment in the rotating section, which in turn permits a reduction in the mass of the supporting structures. If the mass of the supporting structure is linearly proportional to the effective floor load, then reducing one by 50-percent reduces the other by 50-percent. The masses corresponding to these reductions are listed in column 3 of Table 15-1, as Composite Materials, 0.5 Earth Gravity, Standard Atmospheric Pressure. The corresponding relative reductions appear in Figure 15-1. The effect shows a six percent mass reduction in the rotating section which nets a 30 percent combined reduction relative to the baseline.

C. Effects of Reduced Internal Pressure

The life support considerations presented in Section 4 above suggests a means for operation at internal pressures less than Earth sea level equivalent. A reduction to 70-percent standard atmospheric pressure appears reasonable, and is just slightly lower than that of jetliner cabin pressure (Figure 15-2). The mass reductions incurred by pressure decreased derive from a corresponding decrease in atmosphere density and decrease in required shell thickness of the pressurized volumes. In this study a 30-percent pressure reduction translates into a 30-percent reduction in the mass of the atmosphere and pressure shells. The resulting masses are shown in column 4 of Table 15-1, Composite Materials, 0.5 Earth Gravity, 0.7 Standard Atmospheric Pressure. The relative reductions appear in Figure 15-1, and result in a net 40 percent saving in mass to orbit as compared to the baseline value.

These combined effects are considered applicable to large spacecraft in general and underscore the need for definition of an acceptable long-term artificial gravity level.

15.3 Interactive Effects for the Baseline Configuration

Within the ATSS, mass changes in the rotating section must be accommodated by a balancing change in the counterrotators, since the Sun-facing orbit requires a continuous nulling of gyroscopic effects. For the purposes of this study the gyroscopic balance at all times can be expressed.

$$[m_1\, k_1^2 + m_2\, k_2^2]\, w_1 = m_3 k_3^2 w_3$$

where:

Subscript 1 denotes the torus, spokes, and central hub assembly.

Subscript 2 denotes the solar dynamics units.

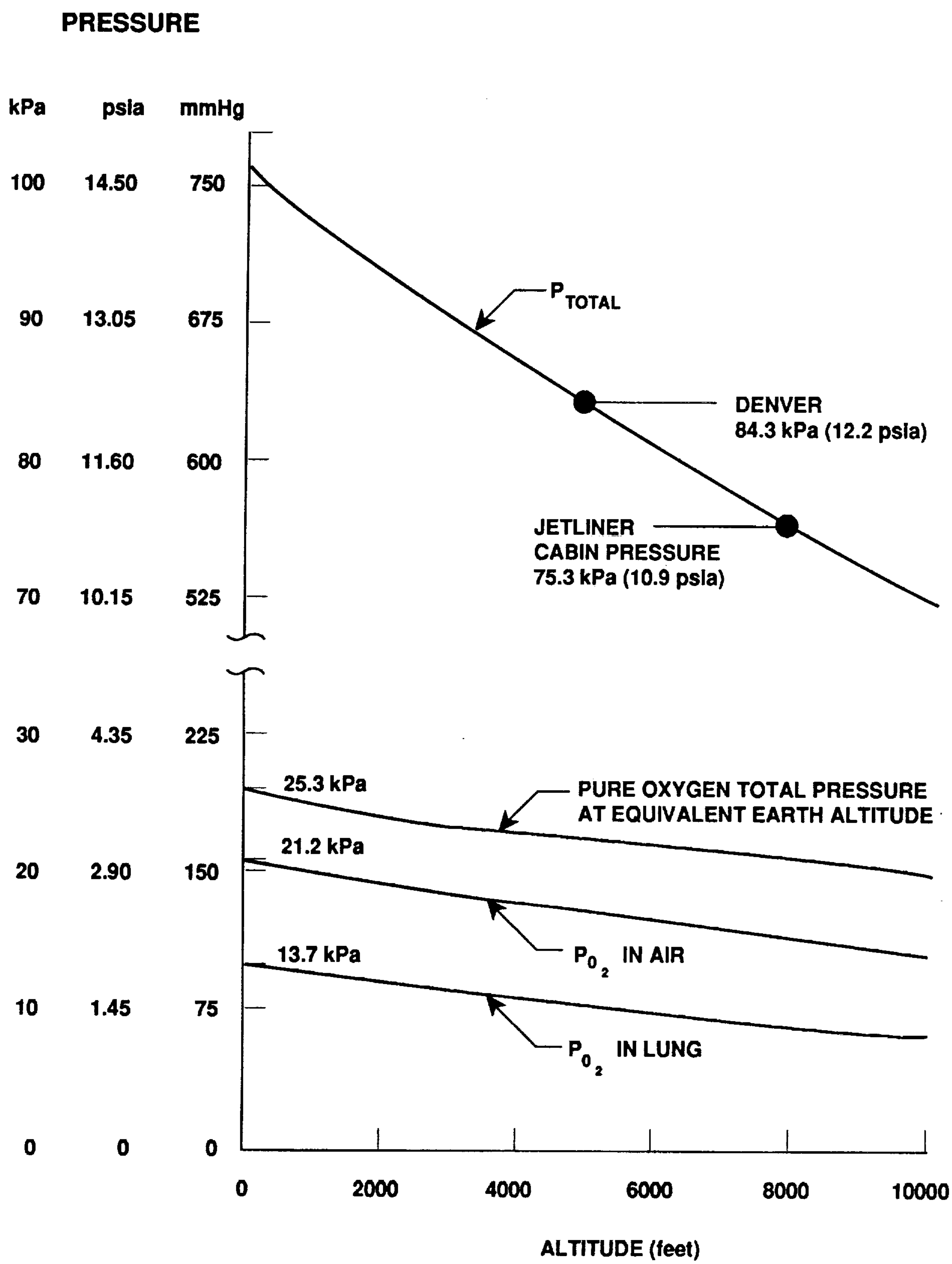


Figure 15-2, Partial Pressure of Oxygen in Air and Lung versus Altitude.

Subscript 3 denotes the counterrotators.

The radii of gyration for the three entities were calculated to be approximately:

k_1 = 106 meters (torus, spokes, central tube)

k_2 = 100 meters (solar dynamics units)

k_3 = 45.5 meters (counterrotators)

The mass m_1 can be related to Table 15-1 as the sum of the masses of all elements in the rotating section except the power which becomes m_2 (solar dynamics units). This equation can be used with mass estimates of the rotating section and radii of gyration noted above to calculate the counterrotator mass required for nulling the angular momentum and for the purposes of this evaluation, the counterrotators operate at 10 rpm, (w_3 = 1.047 rad/sec). The total mass for the baseline ATSS as rotating, stationary, and counterrotators is listed in Table 15-1 under Aluminum Materials, Earth Gravity, Standard Atmospheric Pressure and the contributions from each of the three elements is shown graphically in Figure 15-3. The total mass projection for the entire system identifies the need for improvements.

A. Effects of Advanced Composite Materials

The use of advanced composite materials makes the direct reduction in masses as listed in Table 15-1 for Composite Materials, Earth Gravity Standard Atmospheric Pressure, these values also appear in Figure 15-3. The reduction in the rotating mass also reduces the requirement for inertial balance and results in a larger mass reduction for the counterrotators. Table 15-1 identifies a 704,000 kg (1.55 x 10^6 lb) reduction in the rotating section yielding a 1,060,000 kg (2.34 x 10^6 lb) reduction in the counterrotators. Figure 15-3 shows the combined effects in reducing the mass of the ATSS by just the use of advanced materials.

B. Effects of Reduced Gravity

Operation of the ATSS at an artificial gravity level equal to half Earth changes the torus rotation from 2.8 rpm to 2.0 rpm. A modest mass change in the rotating section

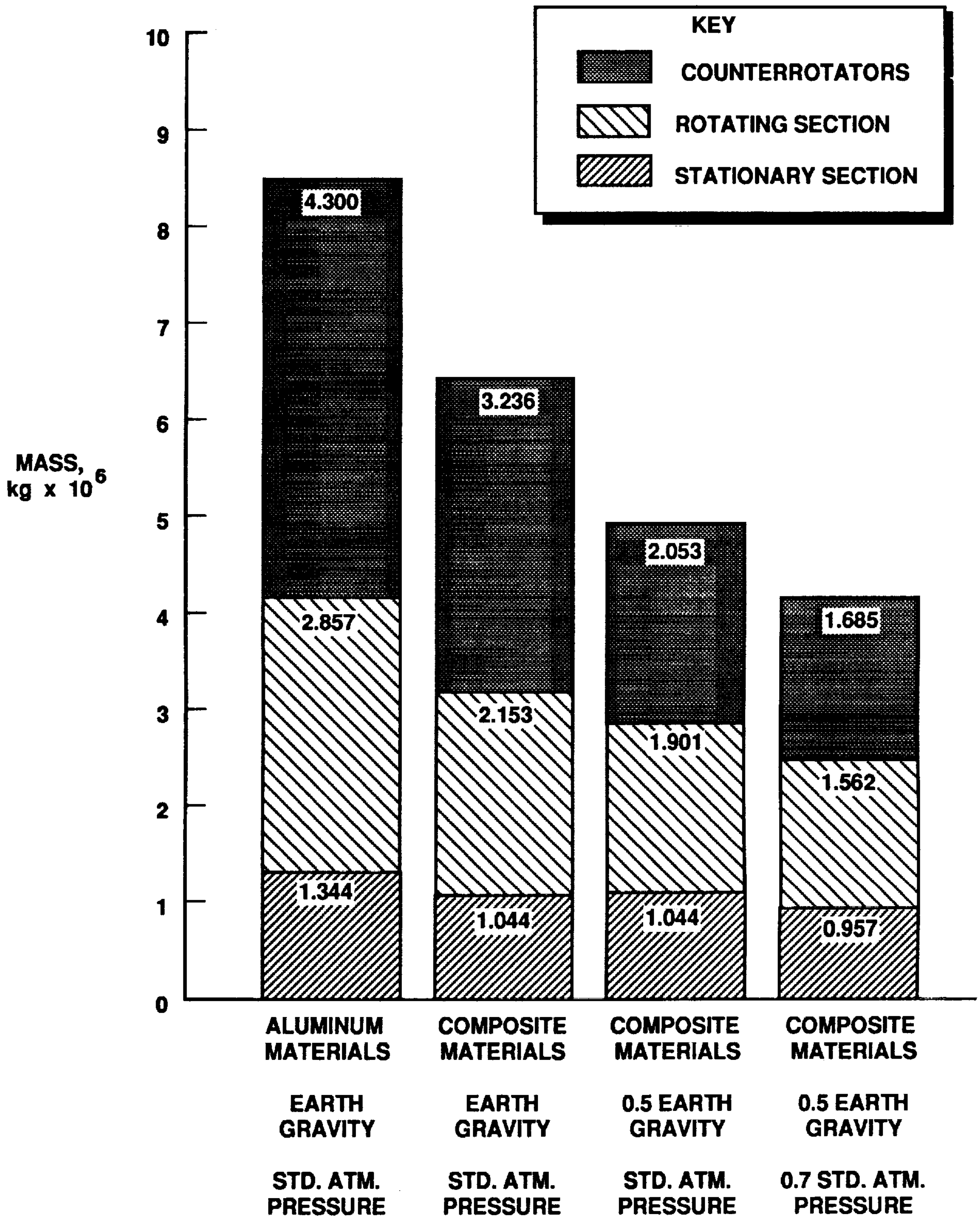


Figure 15-3, Effects of Materials and Operational Changes on the ATSS Mass. Torus Radius is 114.3 meters.

(six percent, 252,000 kg, 555,660 lbs) represents the total for the inhabited areas. On the other hand the changes in balancing mass is significant, and amounts to 1,183,000 kg (2.60×10^6 lb). Table 15-1 lists the masses and Figure 15-3 shows the results graphically for the case of Composite Materials 0.5 Earth Gravity and Standard Atmospheric Pressure.

C. Effects of Reduced Pressure

Reductions in mass due to less atmosphere and thinner pressure shells amounts to 426,000 kg (939,330 lb) such that the combined mass of the rotating and stationary sections are only 60 percent of the baseline value. Reduction in the rotating section is amplified in its effect on the counterrotators which show an additional mass reduction of 368,000 kg (811,440 lb) which brings the total mass for the ATSS to a level about half the baseline value. These effects are listed in Table 15-1 and shown in Figure 15-3 for Composite Materials, 0.5 Earth Gravity, and 0.7 Standard Atmospheric Pressure.

These comparisons illustrate the types of interactions that will occur in a large spacecraft system that involves rotating sections which require nulling of angular momentum. The masses of the rotating section and the counterrotators are interdependent, changes in one reflect into the other with magnitude defined by the configuration.

15.4 Interactions Related to Configuration

The previous examples achieved 0.5 Earth g by slowing the rotation of the torus. An alternative approach could maintain the rotation rate and reduce the major diameter of the torus proportionately. For the purposes of this comparison, the torus rotation rate remains at 2.8 rpm, the radius is reduced to 57.2 m (188 ft) and the two solar dynamic power units are shifted to the platform. All other features remain the same. A revised baseline for ATSS mass is shown in Table 15-2 for the case of Aluminum Materials, 0.5 Earth Gravity, and Standard Atmospheric Pressure, this baseline is also summarized in

TABLE 15-2. EFFECTS OF MATERIALS AND ATMOSPHERIC PRESSURE CHANGES ON THE ATSS MASS FOR A TORUS RADIUS OF 57.2 METERS ROTATING TO PRODUCE 0.5 EARTH GRAVITY. (Masses are in Metric Tons)

Defining Parameters	Aluminum Materials 0.5 Earth Gravity Std. Atm. Press.	Composite Materials 0.5 Earth Gravity Std. Atm. Press.	Composite Materials 0.5 Earth Gravity 0.7 Std. Atm. Press.
ATSS Without Counterrotators			
Rotating Sections			
Pressure Shells	647	453	317
Structures	374	262	262
Equipment	307	215	215
Atmosphere	223	223	156
Variables	197	197	197
Power	0	0	0
Total	1748	1350	1147
Stationary Sections			
Power	273	273	273
Variables	113	113	113
Atmosphere	46	46	32
Equipment	197	138	138
Structures	454	318	318
Pressure Shells	349	244	171
Total	1432	1132	1045
Total ATSS Without Counterrotators	3180	2482	2192
Counterrotators	589	455	387
Total ATSS	3769	2937	2579

Figure 15-4. This configuration, requires much less mass in the counterrotators principally due to the smaller, less massive torus. The conditions defining the counterrotators become

$$m_1 \, k_1^2 \, w_1 \; = \; m_3 \, k_3^2 \, w_3$$

where

k_1 = Radius of gyration for the torus hub and spokes is 49.6 m.

k_3 = Radius of gyration for the counterrotators is 45.5 m.

w_1 = Angular velocity for the torus is 0.298 rad/sec.

w_3 = Angular velocity for the counterrotators is 1.047 rad/sec.

A. Effects of Composite Materials

Use of advanced composite materials results in the same relative (30 percent) reduction in the masses for pressure shells, structure and equipment as in the case for the larger diameter torus. These values are listed in Column 2 of Table 15-2 and illustrated in Figure 15-4. The reduction in mass for the rotating and non-rotating sections amounts to 698,000 kg (1.54 x 10^6 lb); a mass reduction in rotating section has a corresponding but smaller reduction in the requirement for counterrotators. The total reduction in mass delivered to orbit totals 832,000 kg (1.83 x 10^6 lb) and represents a net 22 percent savings.

B. Effects of Reduced Atmospheric Pressure

Lowering the atmospheric pressure also makes the same relative change in the masses for on-board gasses and pressure shells. The results are listed in Table 15-2 and illustrated in Figure 15-3 for Composite Materials, 0.5 Earth Gravity, and 0.7 Atmospheric Pressure. An eased atmospheric pressure requirement results in a net additional mass saving of 358,000 kg (789,400 lb) such that the total mass is 68 percent of the small torus baseline and only 30 percent of the full diameter baseline ATSS.

These comparisons further illustrate the interaction of technology advances and operational considerations. The definition of an advanced space station configuration will

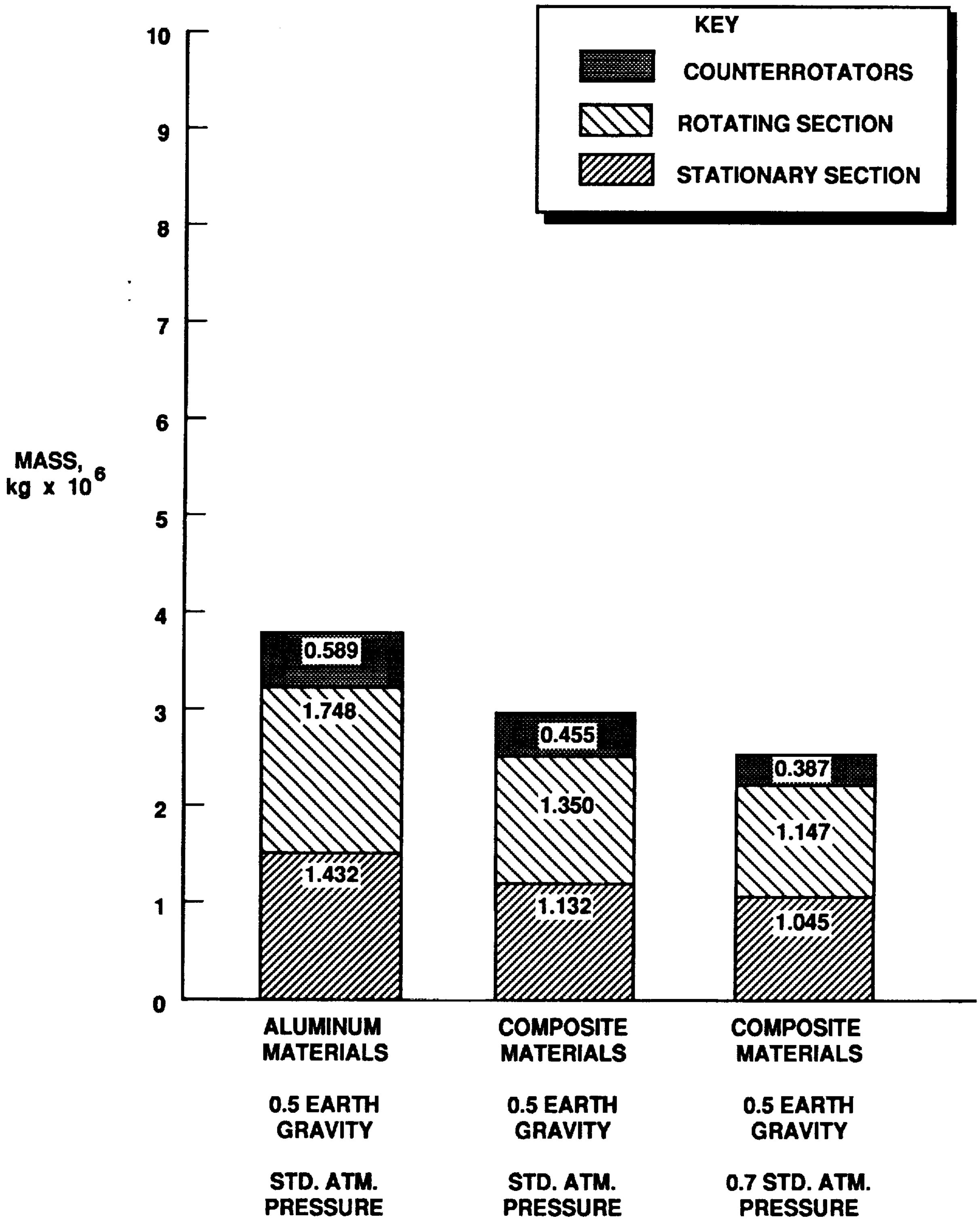


Figure 15-4, Effects of Materials and Operational Changes on the ATSS Mass. Torus Radius is 57.6 meters.

need the advantages offered by improved materials. In addition, the configuration will need to reflect an optimized accommodation of artificial gravity by rotation and internal operating atmospheric pressure. As these examples illustrate, effects combine and amplify in a manner that must be constructively addressed.

16.0 CONCLUSIONS

The studies summarized herein illustrate that a large, Sun-oriented space station such as the ATSS could support the future space mission initiatives. For manned applications, the energy source for such a station remains the Sun. The implementation could follow two paths; either improved solar-photovoltaic conversion coupled with efficient energy storage, or high performance solar-thermal dynamic systems with thermal storage. Each option has intrinsic advantages and disadvantages. If solar cell efficiencies can improve sufficiently, the photovoltaic option appears easiest to implement and will require the development of assembly methods for large area solar arrays.

The rotating feature of the ATSS concept responds to the requirement for long term human presence in space and actually simplifies the operation of some on-board fluid and mechanical functions. The large diameter of the torus allows an earth-equivalent weight condition within a rotation rate acceptable to the human vestibular system. A significant challenge exists in the achievement of attitude stability while operating with large gravity gradient disturbances. Using large counterrotating elements as control moment gyros offers one method for accomplishment and shows the need for further studies into stabilization interactions that involve a number of rotating components. Synergies associated with water usage will also benefit from further studies with emphasis on techniques for efficient electrolysis.

An availability of heavy lift launch vehicle with a large diameter shroud enclosure appears as a key element item for large space vehicles. Alternatives have been examined for the on-orbit assembly of smaller modular elements, but these require a larger number of launches and add additional complexity to the on-orbit assembly process.

The ATSS concepts together with their related supporting technology requirements have been based upon a continuing process of development relative to technical achievements or improved performance. On the other hand, a technology breakthrough in superconductivity, nuclear space power or propulsion could alter the configuration significantly. However, the successful implementation of a large rotating space station will both require and depend upon achievement of the technology advances cited herein.

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15. Supplementary Notes

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16. Abstract

This report summarizes the principal system features defined for the Advanced Technology Space Station and describes the 21 pacing technologies identified during the course of the study. The descriptions of system configurations were extracted from four previous study reports. The technological areas focus on those systems particular to all large spacecraft which generate artificial gravity by rotation. The summary includes a listing of the functions, crew requirements and electrical power demand that led to the studied configuration. The pacing technologies include the benefits of advanced materials, in-orbit assembly requirements, stationkeeping, evaluations of electrical power generation alternates, and life support systems. The descriptions of systems show the potential for synergies and identifies the beneficial interactions that can result from technological advances.

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